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THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

Edited by

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

EDWIN B. FROST
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NOVEMBER 1928

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THE ULTRA-VIOLET BAND SPECTRUM OF NITROGEN

By R. T. BIRGE and J. J. HOPFIELD

ABSTRACT

The ultra-violet emission spectrum of N_2 consists chiefly of a clearly defined system of more than sixty bands, degraded to the red. A number of spectrograms of this system have been obtained with a vacuum spectrograph, and the weighted average wave-length of each band is tabulated, together with the vibrational quantum analysis of the system. The *absorption spectrum* of N_2 also contains this system, and the absorption measurements have been used to determine most accurately the vibrational constants of the upper level.

Numerous emission and absorption bands occur *in addition* to the foregoing system. Among the *emission* bands can be recognized three distinct progressions, representing presumably three new systems. The analysis of each of the three systems indicates that it is due to a transition from a new upper level to the vibrational states of the normal electronic level of the molecule. One of these systems occurs, however, when commercial, partially purified nitrogen is used, but *not* with chemically prepared nitrogen, and its origin is therefore in doubt.

The *intensity distribution* in all four nitrogen systems presents several interesting features, some of which have not been explained. Further study is being made of the many remaining unassigned bands, in emission and in absorption.

From the vibrational constants of the several electronic levels one can calculate approximately the *heat of dissociation* of N_2. Two possible alternatives lead to most probable values of 11.9 and 9.5 volts, respectively.

INTRODUCTION

The ultra-violet band spectrum of nitrogen was first observed by Schumann.[1] Twenty-one of the strongest bands, lying between λ 1383 amd λ 1871, were first measured by Lyman.[2] About four years ago one of the present authors obtained several spectrographs

[1] V. Schumann, *Smithsonian Contributions*, No. 1413, p. 16, 1903.

[2] T. Lyman, *Spectroscopy of the Extreme Ultra-Violet*, pp. 82 and 113, and *Astrophysical Journal*, **33**, 98, 1911.

of the ultra-violet emission spectrum of nitrogen, showing a large number of bands extending from λ 950 toward the visible. Shortly afterward we measured these bands and arranged about thirty of them in a definite system.[1] The vibrational constants for the upper and for the lower levels were found to be different from those of any previously known nitrogen level, so that it was impossible to relate this system to the known nitrogen-band systems, or even to be certain that it was due to nitrogen, since nitric oxide was present in the discharge tube, as shown by the prominence of the gamma bands of *NO*.

About a year later, Sponer[2] noted that the upper level of the gamma bands of *NO* had apparently the same vibrational constants as the lower level of the new system, thus indicating that it was due really to *NO*, and it was so listed by Birge and Sponer,[3] the *C–A* bands of *NO* in Figure 3 of that article representing this system. A few months later, however, Sponer,[4] working in this laboratory, obtained the $n''=0$ progression of this system in absorption in cold nitrogen. Stimulated by this discovery, we made further measurements of the emission spectrum and also obtained a number of spectrograms of the absorption spectrum of nitrogen. The results of this work, reported at the time to the American Physical Society,[5] were: (1) the extension of the main system to include over sixty bands, lying between λ 1249 and λ 2091; (2) the discovery of two new progressions running from two electronic levels to the normal level; (3) the proof that the absorption progression just noted was due really to N_2, but that a second progression observed by Sponer was due to *CO*.

The new absorption spectrograms taken at this time included incidentally two emission exposures. These later spectrograms were taken with a new grating, giving twice the dispersion of the older

[1] R. T. Birge and J. J. Hopfield, *Nature*, **116**, 15, 1925.

[2] H. Sponer, *ibid.*, **117**, 81, 1926.

[3] R. T. Birge and H. Sponer, *Physical Review*, **28**, 259, 1926; see Fig. 3, p. 264. This is also Fig. 26, p. 244, of the National Research Council Bulletin, *Molecular Spectra in Gases*, 1926 (to be referred to as *Report*).

[4] H. Sponer, *Proceedings of the National Academy of Science*, **13**, 100, 1927, and *Zeitschrift für Physik*, **41**, 611, 1927.

[5] R. T. Birge and J. J. Hopfield, *Physical Review*, **29**, 356, 1927.

one, and were therefore more suitable for accurate measurements. No measurements, however, were made from them at that time. Recently we obtained enlargements of these new spectrograms and then noted that the new emission spectrograms differed in several significant aspects from the older films. We have accordingly now made extensive measurements of both emission and absorption spectrograms, and have correlated and examined all the data. Aside from the more accurate evaluation of the molecular constants, this work has brought out several additional facts. There are still a considerable number of bands on our plates for which the analysis is not complete, but it seems best to present, without further delay, the detailed results for the bands which have been analyzed, reserving the others for future study.

APPARATUS

The spectrograph[1] used in obtaining the films discussed in this article is of 50-cm radius of curvature. The earlier films 82 and 83 were procured with a grating ruled with about 15,000 lines per inch, and the later ones, which include 235 and 237, with one of about 30,000 lines per inch, and therefore having twice the dispersion of the first.

The discharge tube used for films 82 and 83 was π-shaped with a total length of about 1 m and about 1 cm diameter. The horizontal part of the tube faced the slit end on. An 11,000-volt, 10-kw transformer with a suitable water resistance in series on the high-voltage side was used for exciting the discharge. "Purified" nitrogen, i.e., commercial nitrogen passed over red-hot copper filings to remove oxygen and then over phosphorus pentoxide to take out moisture, was allowed to flow continuously through a capillary valve[2] into the discharge tube, and was pumped out through the receiver of the spectrograph by means of a high-speed oil pump in series with a mercury-vapor condensation pump. A liquid-air mercury trap was used in the vacuum line between the pump and the receiver. The pressure in the receiver rarely exceeded 0.002 mm. *NO* appears as the most prominent impurity in these spectra, while *CO* seems en-

[1] J. J. Hopfield, *ibid.*, **20**, 573, 1922.

[2] J. J. Hopfield, *Journal of the Optical Society of America*, **12**, 391, 1926.

tirely absent. This accounts in part for the difference between these films and those listed below. Specially prepared ultra-violet films[1] were used, and exposures of several hours were necessary with this grating to give satisfactory results.

Exposures 235_7 and 237_6, shown in the plate, are from two spectrograms taken with the more closely ruled grating, and with a different type of discharge tube, namely, a capillary tube of about 1-mm internal diameter mounted close to the slit of the spectrograph. The same transformer was used as before, but a kenetron was placed in series with it to rectify the current in the case of the emission spectra, and the kenetron and condensers were used to make the heavy instantaneous current necessary for the continuous background of the absorption spectra.[2]

In obtaining the emission picture 235_7 the gas was admitted into the receiver through a capillary valve and pumped out through the slit and discharge tube. The mercury-vapor pump was not used, and consequently the pressure in the receiver was 0.1 mm and that in the discharge tube slightly less than this. In the absorption picture 237_6, the nitrogen was admitted into the receiver also, and pumped out through the discharge tube. The pressure in the receiver was then about 30 cm and that in the discharge tube not more than a few millimeters.

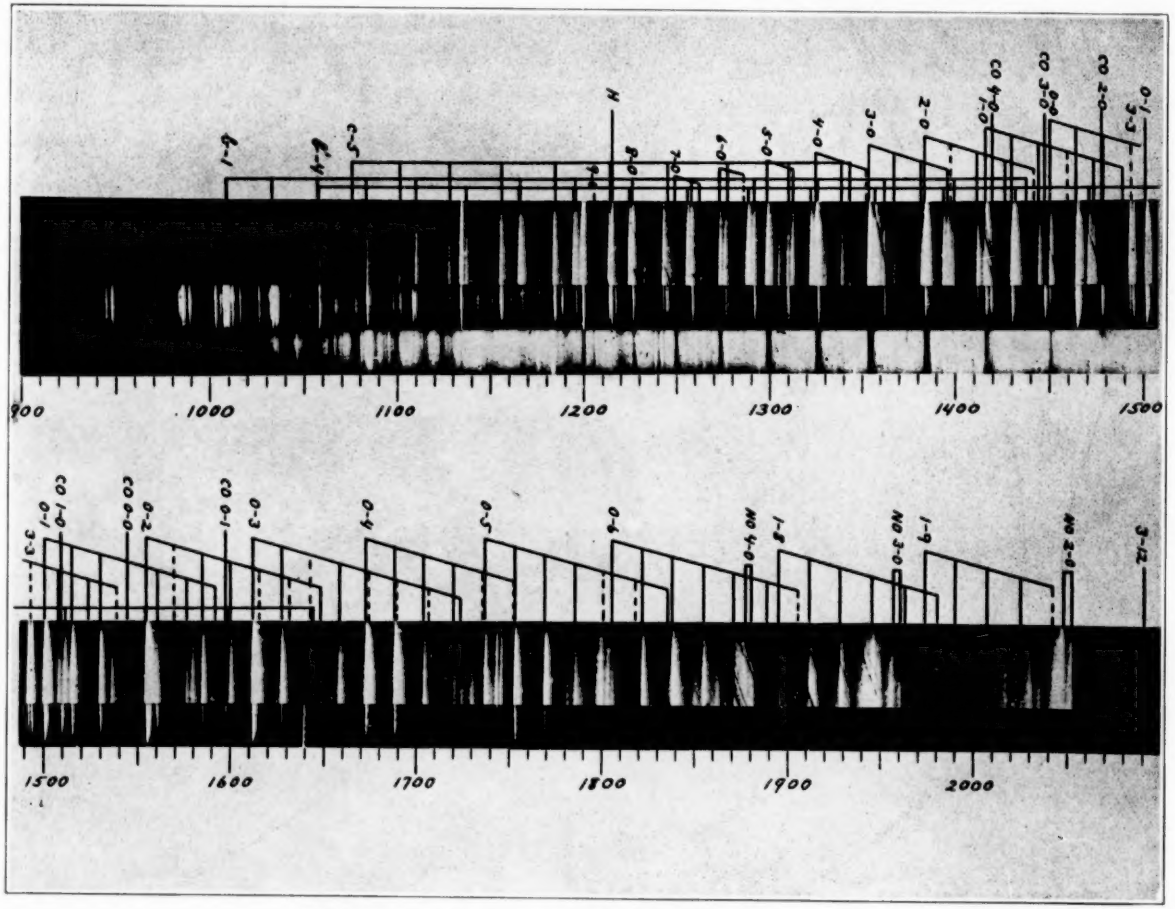
The nitrogen used in these later pictures was obtained by exploding sodium azide, and *CO* and H_2 are noticeably present as impurities, while only a trace of *NO* occurs. By suitable precautions one can get rid of the *CO* and H_2 impurities, but this was not deemed necessary for our purpose. Consequently *CO* is represented both by its emission and absorption spectrum in exposures 235 and 237, while the H_2 bands show clearly in absorption in the latter.

The plate accompanying this article has been prepared from enlargements of three different films, carefully aligned in order to bring out both the similarities and differences. The uppermost strip is from 83_5 (the subscript referring to the number of the exposure on film 83), and shows the first-order emission spectrum of "purified" commercial nitrogen, taken with the 15,000-line grating. As pub-

[1] J. J. Hopfield, *Physical Review*, **20**, 573, 1922.

[2] T. Lyman, *Astrophysical Journal*, **60**, 1, 1924.

PLATE VIII



ULTRA-VIOLET EMISSION AND ABSORPTION SPECTRUM OF N_2

UNIV. OF MICH.

lished, it represents approximately a tenfold enlargement from the original scale of 33.5 A per millimeter. Under it is a portion of exposure 235_7, showing the emission spectrum of the chemically prepared nitrogen, taken in the first order of the 30,000 line grating, having a dispersion of 16.7 A per millimeter. The lowest strip, shown only from 900 to 1500 A, is taken from exposure 237_6, giving the absorption spectrum. All of the analyzed nitrogen bands, discussed later in the paper, are marked at the top of the enlargements, broken lines indicating missing bands. The more conspicuous *CO* bands occurring as impurity only on 235 and 237 are indicated, as well as the 2–0, 3–0, and 4–0 gamma bands of *NO*, occurring only on 83. Other members of this *NO* system appear to the left of each of the foregoing bands. The scale of wave-lengths, laid out with the instrument previously described,[1] is reasonably accurate. Further details regarding the labeling are given later.

MEASUREMENTS

The observed wave-lengths of the sixty or more bands comprising the new ultra-violet system are listed in Table I, column 3. These wave-lengths have been obtained as follows: Spectrogram 83_5 was measured in part by one of us in 1924. Some of the fainter bands have been measured only on this one film. In 1926 extended measurements were made on film 82. As already noted, this resulted in the addition to the system of a large number of bands. Many of the stronger bands were found and measured also in the second order. A few of the strongest appeared in the third order, but, due to a slight lack of definition, were not susceptible to accurate measurement. Recently we have made a complete measurement of exposure 235_7. This spectrogram, having twice the dispersion of 82 and 83, yields measurements with twice the accuracy and four times the weight. It is, however, not possible to get the second order, for the exposure runs only to λ 2750, whereas with the older grating the exposures run to λ 5000. This same spectrogram, 235_7, was measured a second time merely for the classified bands. Finally, the ten bands appearing in absorption were measured on two of the new absorption films.

[1] J. J. Hopfield, *Journal of the Optical Society of America*, **11**, 435, 1925.

TABLE I

1 Band	2 Int. Old	2 Int. 2357	3 Av. λ_{obs}	4 Av. ν_{obs}	5 Wt.	6 O−C	7 ν_{calc}	8 λ_{calc}
						cm^{-1}		
0–0	5	3	1450.09	68961.0	22	− 1.7	68962.7	1450.06
0–1	7	15	1500.72	66634.5	18	+ 2.5	66632.0	1500.78
0–2	9	12	1554.30	64337.7	18	+ 7.5	64330.2	1554.48
0–3	9	12	1611.32	62060.7	14	+ 3.5	62057.2	1611.42
0–4	8	7	1671.74	59817.7	10	+ 4.5	59813.2	1671.87
0–5	5	4	1736.16	57598.4	10	+ 0.4	57598.0	1736.17
0–6	3		1804.65	55412.6	2	+ 0.8	55411.8	1804.67
0–7							53254.4	1877.78
0–8							51125.9	1955.96
1–0	6	6	1415.88	70627.2	22	− 1.1	70628.3	1415.86
1–1	8	15	1464.11	68300.7	14	+ 3.1	68297.6	1464.18
1–2	5	7	1515.17	65999.0	14	+ 3.2	65995.8	1515.25
1–3							63722.8	1569.30
1–4	6	5	1626.51	61481.2	10	+ 2.4	61478.8	1626.58
1–5	9	7	1687.27	59267.5	10	+ 3.9	59263.6	1687.38
1–6	7	7	1751.93	57080.0	10	+ 2.6	57077.4	1752.00
1–7	5	3	1820.83	54919.9	10	− 0.1	54920.0	1820.83
1–8	2		1894.30	52790.1	2	− 1.4	52791.5	1894.24
1–9	0		1973.13	50681.0	1	−10.9	50691.9	1972.70
1–10							48621.2	2056.72
2–0	8	6	1383.76	72267.0	22	− 0.1	72267.1	1383.76
2–1	6	8*	1429.93	69933.5	6	− 2.8	69936.3	1429.87
2–2	2		1478.24	67648.2	2	+13.7	67634.5	1478.53
2–3	5	6	1529.94	65362.3	14	+ 0.7	65361.6	1529.95
2–4	5	5	1584.37	63116.5	10	− 1.0	63117.5	1584.35
2–5							60902.4	1641.97
2–6	4	1	1703.26	58710.7	10	− 5.4	58716.1	1703.11
2–7	6	4	1768.09	56558.3	10	− 0.4	56558.7	1768.07
2–8	5	3	1837.19	54431.1	10	+ 0.8	54430.3	1837.22
2–9	4		1910.99	52328.8	2	− 1.9	52330.7	1910.92
2–10	1		1989.91	50253.6	1	− 6.4	50260.0	1989.65
2–11							48218.1	2073.91
3–0	8	4	1353.61	73876.7	22	− 2.1	73878.8	1353.57
3–1							71548.0	1397.66
3–2	4	3	1444.25	69240.3	10	− 5.9	69246.2	1444.12
3–3							66973.3	1493.13
3–4	0		1544.57	64743.1	1	+13.9	64729.2	1544.90
3–5	4	3	1599.68	62512.5	10	− 1.6	62514.1	1599.64
3–6	4		1657.67	60325.6	2	− 2.2	60327.8	1657.61
3–7	2		1719.63	58152.0	1	−18.4	58170.4	1719.09
3–8	3		1784.56	56036.2	2	− 5.8	56042.0	1784.38
3–9	4	1	1853.92	53939.7	6	− 2.7	53942.4	1853.83
3–10	4		1927.84	51871.4	2	− 0.3	51871.7	1927.83
3–11	2		2007.43	49815.0	1	−14.8	49829.8	2006.83
3–12	1		2090.43	47837.0	1	+20.1	47816.9	2091.31
3–13							45832.9	2181.84

TABLE I—*Continued*

1 Band	2 Int. Old	2 Int. 2357	3 Av. λ_{obs}	4 Av. ν_{obs}	5 Wt.	6 O−C	7 ν_{calc}	8 λ_{calc}
						cm^{-1}		
4–0	6		1325.16	75462.7	14	− 0.5	75463.2	1325.15
4–1	2		1367.30	73136.7	2	+ 4.2	73132.5	1367.38
4–2	5		1411.59	70842.0	2	+11.4	70830.6	1411.82
4–3							68557.7	1458.62
4–4	3		1507.93	66316.0	2	+ 2.3	66313.7	1507.98
4–5	3	5*	1559.97	64103.7	6	+ 5.2	64098.5	1560.10
4–6							61912.2	1615.19
4–7							59754.9	1673.50
4–8							57626.4	1735.31
4–9							55526.8	1800.93
4–10	4		1870.95	53448.8	2	− 7.3	53456.1	1870.69
4–11	4		1944.84	51418.0	2	+ 3.7	51414.3	1944.99
4–12	2		2024.62	49392.0	1	− 9.3	49401.3	2024.24
4–13							47417.3	2108.94
5–0	5		1298.37	77019.9	10	− 0.2	77020.1	1298.36
5–1	4		1339.28	74667.0	2	−22.4	74689.4	1338.88
5–2	2		1382.04	72357.6	2	−30.0	72387.6	1381 45
5–3	1		1426.63	70095.2	2	−19.4	70114.6	1426.23
5–4	4		1473.40	67870.0	1	− 0.6	67870.6	1473.39
5–5	1		1523.55	65636.0	1	−19.4	65655.4	1523.10
5–6	3		1575.86	63457.5	2	−11.7	63469.2	1575.57
5–7							61311.8	1631.01
5–8							59183.3	1689.67
5–9							57083.7	1751.81
5–10							55013.0	1817.75
5–11	0		1888.36	52956.0	1	−15.2	52971.2	1887.82
5–12	1		1963.13	50939.0	1	−19.3	50958.3	1962.39
5–13							48974.3	2041.89
6–0	4		1273.13	78546.5	10	− 2.9	78549 4	1273.08
6–1	4		1312.32	76200.9	2	−17.7	76218.6	1312.01
6–2							73916.8	1352.87
6–3	3		1396.04	71631.0	2	−12.9	71643.9	1395.79
6–4							69309.8	1440.93
6–5	2		1488.72	67172.0	1	−12.7	67184.7	1488.43
6–6							64998.4	1538.50
6–7	0		1591.75	62824.0	1	−17.0	62841.0	1591.32
6–8	1		1647.66	60692.0	1	−20.6	60712.6	1647.10
6–9							58613.0	1706.11
6–10							56542.3	1768.59
6–11	1		1835.50	54481.0	1	−19.4	54500.4	1834.85
6–12							52487.5	1905.21
6–13							50503.5	1980.06
7–0	1		1249.25	80047.7	9	− 3.0	80050.7	1249.21
7–1							77720.0	1286.67
8–0	(Abs.)		1226.63	81524.0	8	+ 0.1	81523.9	1226.63
8–1	1		1262.86	79185.0	1	− 8.2	79193.2	1262.73
9–0	(Abs.)		1205.27	82969.0	4	+ 0.2	82968.8	1205.27

* = Blend.

The wealth of experimental material thus collected has not been an unmixed blessing, since the measurements on one film, while reasonably consistent among themselves, have not always agreed with those of the other films. Part of the inconsistency has been traced to the unavoidable personal equation present in the measurement of any band head. Thus on films 82 and 83, as can be seen clearly on the plate, the heads of the stronger bands have a distinctly bowed appearance. In the original measurements, it was assumed that this bulging was a result of irradiation, and an attempt was made to allow for it. On the other hand, the new spectrograms 2357 and 2358 show the bands with a much straighter edge, making the setting more certain. The measured frequencies, however, were found to average about 6 cm^{-1} less than the older measurements, even for bands close to standard lines, where errors due to film distortion are necessarily eliminated. A remeasurement of selected portions of the older films, this time making no allowance for irradiation, then gave results in perfect agreement with the new measurements. Because of this, we have arbitrarily raised by 6 cm^{-1} the weighted average frequency of each band, as obtained from Plates 82 and 83.

A similar constant discrepancy of 3 cm^{-1} has been found between the absorption and emission measurements on the new plates. This is of course a small quantity, equaling only 0.063 A at λ 1450, or 0.004 mm on the new plates. The absorption frequencies are the higher, as if each band head spread somewhat to the violet (the bands being themselves degraded to the red). This seems to be a common phenomenon in absorption spectra. We have decided to use the emission spectrum as a basis for the measurements, and have accordingly lowered by 3 cm^{-1} the weighted mean of each absorption frequency. The final weighted averages, together with each weight, are given in Table I, columns 3 and 5. The first order of the older plates is weighted 1, and the first order of the new plates or the second order of the older is weighted 4.

All of the spectrograms contain a number of standard lines, on which the measurements have been based. For these lines, beginning with the 1926 work, new wave-lengths have been obtained and used. These new wave-lengths are based primarily on the λ 1215.68

line of hydrogen, which appears in four orders on the older plates. All of the standard lines appear in at least two orders (with the exception of *Hg* 2537), and some of them in three, making possible a fairly accurate and consistent set of measured values. The lines with their adopted values are given in Table II. For comparison we give the older values of most of these lines, as obtained by one of us.[1] Since the data given in this paper were obtained, one of us[2] has procured very accurate new measurements for certain of the foregoing lines, with a ten-foot vacuum spectrograph, using the second and third orders of the lines against iron standards. The new wave-lengths are λλ 1742.749, 1302.202, 1304.871, and 1306.041. The use of these wave-lengths would reduce slightly the observed *minus* calculated values of Table I, but not by enough, it is believed, to justify the necessary labor of revision.

The probable relative accuracy of our measurements can better be discussed after considering the theoretical results. The wave-lengths of the other nitrogen systems, listed in Tables III, IV, and V, are based on the same standard lines, and need no separate explanation.

THE NEW NITROGEN-BAND SYSTEM

This system consists of a number of clearly defined bands, degraded to the red. The original published equation for the system,[3] based on about thirty bands, is

$$\nu = 68956.6 + (1681.45n' - 15.25n'^2) - (2345.16n'' - 14.445n''^2) \; . \quad (1)$$

The $f(n')$ of this equation is uncertain, being based on bands covering the short range $n' = 0$ to 3. The most direct method of obtaining such a $f(n')$ is from the absorption spectrum. In the present case, as shown on the plate, this latter spectrum runs from $n' = 0$ to $n' = 9$, inclusive (with $n'' = 0$). The two independent sets of absorption measurements already mentioned are in very close agreement, and the differences of successive bands give a remarkably smooth but *non-linear* $\omega_n : n$ curve. Previous to these measurements it had not been certain whether or not this curve was linear. Equation (1),

[1] J. J. Hopfield, *Physical Review*, **27**, 801, 1926 (abstract 25).

[2] J. J. Hopfield, unpublished.

[3] R. T. Birge and J. J. Hopfield, *Nature*, **116**, 15, 1925.

with its parabolic $f(n')$, corresponds of course to a linear $\omega_n : n$ curve. The 1926 measurements, based on emission bands extending from $n'=0$ to 8, indicated the need of an additional term, and this result

TABLE II

1 Adopted λ	2 Older λ	3 Source	4 Notes
1025.73	.....	Hydrogen	Calculated λ
1134.18	1133.97	Nitrogen $1S-2P''$ triplet	Adopted λ due to Bowen and Ingram*
1134.42	1134.21		
1134.98	1134.78		
1134.31	1134.09	.....	Center of gravity of first two lines
1167.45	1167.32	Nitrogen $1S-3P''$ doublet	
1168.50	1168.37		
1176.52	1176.40	Nitrogen $1S-3P$ doublet	
1177.73	1177.59		
1199.59	1199.53	Nitrogen $1S-2P$ triplet	
1200.24	1200.19		
1200.69	1200.66		
1215.68	.....	Hydrogen	Calculated λ
1302.21	1302.27	Oxygen resonance triplet	
1304.92	1304.96		
1306.06	1306.12		
1492.70	1492.61	Nitrogen $1S-2P''$ doublet	
1494.71	1494.57		
1742.81	1742.81	Nitrogen $1S-2P$ doublet	
1745.32	1745.35		
2537.281	.....	Mercury	Accepted I.A. value reduced to vacuum

* I. S. Bowen and S. B. Ingram, *Physical Review*, **28**, 444, 1926.

is quoted by Sponer.[1] Even in this case, however, the faintness of the bands above $n'=4$ makes the resulting $f(n')$ quite uncertain, and a parabolic $f(n')$ was found practically as satisfactory. The new $f(n')$, obtained from the absorption data, is appreciably different from both of the older results, but fits the emission data as well as can be expected. As applied to the absorption measurements the

[1] *Proceedings of the National Academy of Science*, **13**, 100, 1927, and *Zeitschrift für Physik*, **41**, 611, 1927.

average observed *minus* calculated value is only 0.46 cm^{-1} (=0.008 A=0.0005 mm on the film).

Throughout all the successive measurements the original $f(n'')$ of equation (1) has been found quite satisfactory and has accord-

TABLE III

1 Band	2 Int. 2357	3 λ_{obs}	4 ν_{obs}	5 O−C	6 λ_{calc}
	First Head: *c* Series				
				cm^{-1}	
c−0	.....	.....	.....	.....	957.90
c−1	.....	.....	.....	.....	979.78
c−2	.....	.....	.....	.....	1002.38
c−3	.....	.....	.....	.....	1025.76
c−4	.....	.....	.....	.....	1049.92
c−5	2−	1075.13	93,012	−17.9	1074.92
c−6	3	1100.88	90,836	− 7.7	1100.79
c−7	4	1127.53	88,689	+ 2.7	1127.57
c−8	6	1155.27	86,560	+ 2.2	1155.30
c−9	7	1183.95	84,463	+ 4.8	1184.02
c−10	5	1213.81	82,385	− 2.5	1213.78
c−11	4	1244.57	80,349	+ 3.3	1244.62
c−12	3	1276.50	78,339	+ 6.2	1276.60
c−13	4*	1309.17	76,384	+35.3	1309.78
c−14	.....	.....	.....	.....	1344.20‡
	Second Head				
c−0	.....	.....	.....	.....	958.60
c−1	.....	.....	.....	.....	980.51
c−2	.....	.....	.....	.....	1003.15
c−3	.....	.....	.....	.....	1026.55
c−4	.....	.....	.....	.....	1050.76
c−5	2	1075.80	92,954	± 0.0	1075.80
c−6	4	1101.75	90,765	− 2.7	1101.71
c−7	4	1128.58	88,607	− 3.4	1128.54
c−8	6	1156.35	86,479	− 2.9	1156.31
c−9	7	1185.04	84,385	+ 2.7	1185.08
c−10	.....	†	.....	.....	1214.90
c−11	4	1245.74	80,274	+ 4.2	1245.79
c−12	3	1277.81	78,259	+ 2.1	1277.84
c−13	5*	1310.34	76,316	+43.2	1311.08

*=Blend. † On *H* 1215.68. ‡ Appears on 83 only.

ingly not been changed. The most accurate test of this $f(n'')$ is obtained from the additional systems listed in Tables III, IV, and V, and discussed in a later section. The final adopted equation of the new system is

$$\nu = 68962.7 + (1678.959n' - 13.3181n'^2 - 0.035353n'^3) - (2345.16n'' - 14.445n''^2) . \quad (2)$$

The observed *minus* calculated values, based on this equation, are listed in column 6 of Table I. They are all well within the limits of

TABLE IV

1 Band	2 Int. 2357	3 λ_{obs} 2357	4 ν_{obs}	5 O−C cm^{-1}	6 λ_{calc}
b–0					985.52
b–1	5	1008.62	99,145	+6.5	1008.69
b–2	10	1032.57	96,846	+9.4	1032.67
b–3	10	1057.38	94,573	+9.3	1057.49
b–4	10	1083.13	92,325	+5.3	1083.19
b–5	5	1109.86	90,101	−3.5	1109.82
b–6		Missing			1137.42
b–7	2	1165.95	85,767	+6.1	1166.03
b–8	5	1195.74	83,630	−2.4	1195.71
b–9	9	1226.43	81,537	+4.2	1226.50
b–10	9	1258.41	79,465	+2.9	1258.46
b–11	9	1291.71	77,417	−3.3	1291.65
b–12	9	1326.17	75,405	−2.3	1326.13
b–13	7	1361.99	73,422	−1.3	1361.97
b–14	4	1399.30	71,464	−4.1	1399.23
b–15	2	1437.98	69,542	+0.1	1437.98

TABLE V

1 Band	2 Int. 82_4	3 λ_{obs}	4 ν_{obs}	5 O−C	6 λ_{calc}	7 Notes
				cm^{-1}		
b'–0					964.53	
b'–1					986.71	
b'–2					1009.64	
b'–3					1033.35	
b'–4	3	1057.72	94542.8	+14.6	1057.89	+b–3 ?
b'–5	4	1083.30	92310.8	− 2.2	1083.27	+b–4 ?
b'–6	4	1109.63	90119.8	− 7.0	1109.55	+b–5 ?
b'–7	4	1136.76	87969.2	− 0.2	1136.76	
b'–8	5	1165.12	85828.2	−12.7	1164.95	
b'–9	5	1194.23	83736.0	− 5.3	1194.15	
b'–10	5	1224.41	81672.0	+ 1.3	1224.43	
b'–11	5	1255.77	79632.8	+ 4.0	1255.83	
b'–12	5	1288.26	77624.1	+ 8.2	1288.40	
b'–13	4	1322.20	75631.5	− 0.4	1322.19	
b'–14	6	1356.93	73696.0	+19.2	1357.28	Blend?
b'–15	4	1393.48	71763.0	+12.5	1393.72	
b'–16	5	1431.18	69872.5	+19.4	1431.57	
b'–17	5	1470.41	68008.0	+23.3	1470.92	
b'–18	4	1511.14	66175.0	+29.9	1511.83	
b'–19					1554.38	
b'–20	1	1597.65	62592.0	+39.4	1598.66	
b'–21	0	1644.06	60825.0	+25.3	1644.75	

experimental error. The chief discrepancies occur in the case of very faint bands, and particularly in those comprising the progressions $n'=5$ and 6. Most of these latter bands have been measured only on exposure 83_5, in 1924, and this set of measurements differs systematically from the later results.

The distribution of intensity in this band system, as observed on spectrograms 82_2 and 83_5, is given in the form of an $n'n''$ diagram in Figure 1. The distribution of intensity is slightly different on the newer films, and therefore in column 2 of Table I we list the intensity from the older films, followed by that from film 235_7. Bands 8–0 and 9–0 are observed only in absorption.

n'/n''	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0	5	7	9	9	8	5	3							
1	6	8	5		6	9	7	5	2	0				
2	8	6	2	5	5		4	6	5	4	1			
3	8		4		0	4	4	2	3	4	4	2	1	
4	6	2	5		3	3					4	4	2	
5	5	4	2	1	4	1	3					0	1	
6	4	4		3		2		0	1			1		2?
7	1													
8		1												
9														

FIG. 1.—Intensity distribution, new nitrogen band system.

Each band of this system is indicated on the plate, all of the bands of a given sequence being connected together by a slanting line, and only the first band being labeled with its n'–n'' value. Thus in the $n''-n'=1$ sequence, the successive bands are 0–1, 1–2, 2–3, 3–4, etc.

In general, the intensity distribution is that to be expected on the Franck-Condon theory.[1] There are, however, many irregularities. Thus there are a number of missing bands, such as 1–3, 2–5, 4–3, 4–8, 5–7, 5–10, 6–2, 6–4, and 6–9. In the case of each of these bands, the calculated wave-length indicates that the band is really missing and not merely concealed or blended with some other band. Irregularities of this character have been observed in other systems, such as the beta bands of *NO*,[2] but the irregularities in the present system seem unusually conspicuous. Thus far no adequate theory has been proposed to account for them.

ADDITIONAL NITROGEN-BAND SYSTEMS

As can be seen from the plate, there are present on our spectrograms, in addition to the band system just considered, a large num-

[1] E. U. Condon, *Physical Review*, **28**, 1182, 1926, and *Report*, pp. 134–141, 248–249.

[2] See p. 138 and Fig. 15 of *Report*.

ber of bands or at least hazy lines. From a study of the older plates we were able to arrange in two progressions some of these bands, degraded to the red like the previous system. The lack of similarity of appearance and the intensity distribution both indicated that each progression represented an independent electronic system. The spacing of the successive bands, in each case, agreed within limits of error with the spacing of the vibrational levels of the normal state of N_2. This showed that these two new systems represented transitions from two new electronic levels to the normal level, and assuming that in each case the upper level is one of zero vibration, we thus locate the two electronic levels. This result was published[1] in 1927. On the plate these two progressions are marked c and b', respectively, the successive bands being connected by a horizontal line and only the first observed member of the progression being specifically labeled. The average observed wave-lengths (including measurements from the newer plates) are listed in Tables III and V.

Probably the most interesting feature of the newer plates, and the one which instigated the recent investigation, is the complete absence of the b' progression! The significance of this will be considered later. Furthermore, there occurs on the older plates what seemed to be at first sight a second component of the b' series which it was found difficult to measure accurately. This second component is present with great intensity on the newer plates, and, due to the absence of the b' series, can there be measured with considerable certainty. The result of the measurements shows that this second component is really an independent progression, having again the intervals of the normal state of N_2. We call it the b series. The observed wave-lengths, as measured only on the newer plates, are given in Table IV. As shown by Tables IV and V, and by the plate, the two progressions practically coincide at λ 1083 (b–4 or b'–5), but the b series lies to the red of b' as one passes toward the red, and to the violet of b' as one passes toward the violet. The b and b' series therefore do not form regular doublets, but merely happen to be in close proximity over a certain limited region.

Tables III, IV, and V give, in addition to the average observed wave-lengths, the corresponding frequency, the intensity, the ob-

[1] R. T. Birge and J. J. Hopfield, *Physical Review*, **29**, 356, 1927.

served *minus* calculated values, and the calculated wave-lengths. These latter two columns are based on the following equations:

$$c \text{ series} \ldots\ldots \nu = \left.\begin{matrix} 104394.6 \\ 104318.7 \end{matrix}\right\} - f(n'') , \tag{3}$$

$$b' \text{ series} \ldots\ldots \nu = 103677.7 \; - f(n'') , \tag{4}$$

$$b \text{ series} \ldots\ldots \nu = 101469.2 \; - f(n'') , \tag{5}$$

where in each case the $f(n'')$ is that of equation (2), i.e., the vibrational energy function of the normal state of neutral N_2. Tables III, IV, and V show that with the possible exception of certain bands near the ends of the series the agreement is remarkably good. From $n''=1$ to 15, the best verification of the $f(n'')$ of equation (2) is to be found in these new progressions. Beyond $n''=15$, the b' series shows a nearly constant discrepancy in the observed *minus* calculated values which has not been explained.

The intensity distribution in these three new systems is very interesting. The b series occurs on both the older and the newer plates, and appears on all plates as a set of bands, with a single head, degraded to the red. In the case of b–1 to b–5, however, the bands are so short that they appear on the older plates almost as lines. On the newer plates they show better the degradation to the red. The intensity of the successive members of the b series rises to a maximum at about b–3, falls to zero at b–6 (λ 1137 calc.), and then rises to a second maximum at about b–10. The general intensity distribution on an $n'n''$ diagram, as explained on the Franck-Condon theory, allows a double maximum of intensity, separated by a pronounced minimum, in the case of any n'' progression, *except* that for $n'=0$. The most plausible assumption, however, in the case of isolated progressions like this, unless excited under very special conditions, is that the upper level is one of zero vibration, and *if* this is the case for the b series, the intensity distribution is, we believe, without precedent. There can hardly be a question that bands b–1 to b–5 form the continuation of the series. As a matter of fact, we first recognized and fitted the bands b–7 to b–15. We then calculated the b–1 to b–5 bands and *afterward* found each one in precisely the calculated position. No further change of the formula in equation (5) was made.

The c series exhibits an intensity distribution of a more nearly normal type, as far as the relative intensity of successive bands is concerned. The single maximum at about c–9 is characteristic of an n'' progression, with $n'=0$, provided the moment of inertia of the upper level is considerably larger than that for the lower.[1] On the other hand, the intensity distribution in each apparent band seems to be directly contradictory to this conclusion. On the older film 83, as shown on the plate, the c series, like the b and b' series, seems to consist of single bands, degraded to the red. But on the newer plate, 2357, each c band consists of a sharply defined and essentially symmetrical doublet. The two members of the doublet are not, however, as sharp as the known lines on the plate, and there can be no question as to their band character. Many doublet bands like this have been observed by the writers in the emission and absorption spectrum of carbon monoxide.[2] In these cases the explanation is clearly as follows. The frequency of vibration, and hence presumably the moment of inertia, is almost identical in the upper and lower levels. The P and R branches of each band should thus consist of essentially equally spaced lines, and the entire band, under low dispersion, has the appearance of a symmetrical doublet, providing no Q branch is present. The well-known near infra-red bands of molecules like HCl exemplify a somewhat similar condition.

If, however, there is a *small* change in the moment of inertia during the band emission, the 0–0 band should be very strong compared to the 1–0 or 0–1, and these in turn strong compared to 2–0 or 0–2. This condition is found in the CO systems just mentioned, but, as noted, is quite the reverse of the condition of affairs in the c series of N_2. Each band of this series was measured at five different points, i.e., the violet edge of each head considered as a double band, the center of each component considered as a symmetrical doublet, and finally the center of the two components, giving the origin of the band under the latter interpretation. Of the resulting five sets of measurements, that for the violet edge of the head of greater wave-length gave much the smallest and most consistent set of observed *minus* calculated values. The symmetrical doublet in-

[1] E. U. Condon, *ibid.*, **28**, 1182, 1926, and *Report*, pp. 134–141, 248–249.

[2] J. J. Hopfield and R. T. Birge, *ibid.*, **29**, 922, 1927 (abstract 80).

terpretation did not give a particularly satisfactory result. Taken in connection with the intensity distribution, this seems to indicate that the c series consists of a double-headed band, the second head being possibly a Q-branch head, and so giving a better set of observed *minus* calculated values. It must be admitted, however, that the separation of the two heads is very large, if considered as R- and Q-branch heads. We may have merely an apparent double electronic level.

In Table III the observed wave-lengths refer to the violet edge of each of the two heads. On the plate we have marked the center of each of these double bands. The successive frequency separations of the two heads, from c–5 to c–13, are 58, 71, 82, 81, 78, —, 75, 80, and 68 cm^{-1}. The last band (c–13) is undoubtedly a blend. With the exception, then, of c–5, the frequency separation is essentially constant, and is so assumed in equation (3) and in the resulting observed *minus* calculated values, and in the calculated λ, of Table III. c–14 occurs only on the older films. It is marked on the plate.

The third set of bands, labeled the "b' series," is found as noted only on the earlier plates. Since these plates show strongly the gamma bands of *NO*, while the later plates do not, one obvious assumption is that the b' series is due to *NO*. But the agreement of the band intervals with the nitrogen vibrational intervals, at least from b'–4 to b'–13, seems almost to preclude this possibility. On the other hand, it is known that the A level of *NO* has almost the same $f(n'')$ as the normal level of N_2, and this caused the earlier incorrect assignment of the new N_2 system to *NO*. Unfortunately, the vibrational levels of the A state of *NO* (the upper state of the gamma bands) are known only to $n=4$, and it is therefore quite impossible to predict reliable values for the range $n=4$ to 21, in which we are interested. The b' series consists of a set of single bands degraded to the red. The intensity of the successive bands is practically constant over a long region, but may be said in general to rise to a maximum near the center of the series (rather than at either end). Because of the non-appearance of this series on the newer plates, we do not wish to affirm that it is due to N_2, rather than to *NO*, but we believe the preponderance of evidence is at present in favor of N_2. The entire appearance of plate 235_7 is that of a low-temperature

intensity distribution, as contrasted with a much higher temperature for Plate 8_{35}. The evident difference in excitation conditions may be the cause of the non-appearance of the b' series, rather than the comparative purity of the nitrogen.

Through the kindness of Professor K. T. Compton, we have very recently had the privilege of examining unpublished plates and measurements of the ultra-violet spectrum of nitrogen, made by K. T. Compton and J. C. Boyce. The spectra are emitted as a result of controlled electron impacts, and contain, in the region λλ 950–1100, about thirty lines, or more probably bands, found also on our plates. Moreover, their plates show many bands and lines below λ 950, indicating that the fading out of our plates, beginning at about λ 1000, is due to absorption. Our own absorption plates taken at very low pressure verify this. At the present time these two additional sources of data have not been examined in sufficient detail to furnish new information regarding the band series under discussion. We hope, however, to use them in connection with future work on this spectrum.

GENERAL DISCUSSION

The four nitrogen-band systems discussed in this paper evaluate four new electronic levels of the neutral N_2 molecule. The levels associated with the familiar first, second, and fourth positive groups of nitrogen have been designated[1] A, B, C, and D. These four new levels are quite distinct from the older four levels, and are here designated a, b, b', and c. The a level lies certainly at 68962.7 cm^{-1} above the normal (X) level, to within a few cm^{-1}. The positions of the b, b', and c levels are given by equations (5), (4), and (3), *provided* we assume that the upper level of the several series is one of zero vibration. The a–X bands occur in absorption, as shown on the plate. We have not as yet found in absorption bands definitely connected with the other three levels, but this aspect of the investigation has not been completed. One of our absorption spectrograms, taken at a pressure of only 0.06 mm, shows numerous strong absorption bands below λ 1000, as already noted.

All of the now-known electronic levels of N_2 are drawn to scale

[1] R. T. Birge, *Nature*, **114**, 642, 1924.

in Figure 2. Each is accompanied by the known vibrational levels. At the left of the figure is given the energy scale, in terms of both volts and cm^{-1} units. Beside each electronic level is given the vibrational frequency ω_0 (on the old quantum theory) where it is known. The probable character of each level is also marked. The X' level is the normal level of N_2^+. The relative position of levels A, B, C, and D is accurately known, but the absolute position is still based on Sponer's[1] determination of excitation potentials and is uncertain to 0.3 volts. As already discussed, the b' level may be false.

The absence of all combinations between the older, capital-letter levels, and the newer, small-letter levels, makes it seem probable that, similar to *CO*, the first group of levels represents a triplet system, and the second a singlet system. It is, however, the purpose of this paper to present the experimental data leading to the establishment of the new levels rather than to discuss critically their character. The many unclassified bands, some in emission and others in absorption, appearing on our plates, point to the existence of several other electronic levels in the neutral N_2 molecule.

As a result of the evaluation of the vibrational energy constants of the normal state of nitrogen, it is possible to calculate, at least approximately, the heat of dissociation of the molecule. Using the linear extrapolation method of Birge and Sponer,[2] the result is 11.75 volts, as already quoted by these writers at a time when this system was assigned to nitric oxide. The $f(n')$ for the upper level (a), newly derived from data on absorption bands, is given in equation (2). A strict extrapolation of the resulting parabolic ω_n curve leads to 5.73 volts, as compared to 5.44 volts, with use of the older equation (1), and to 5.13 volts, given by the 1926 measurements and quoted by Sponer.[3] Adding 5.73 volts to the electronic energy of 8.51 volts (68962.7 $cm^{-1} \div 8100$), we obtain 14.24 volts. It is known from the work of one of us[4] that the nitrogen atom has a metastable state of 2.39 volts energy. Assuming the products of dissociation from level

[1] H. Sponer, *Zeitschrift für Physik*, **34**, 622, 1925.

[2] R. T. Birge and H. Sponer, *Physical Review*, **28**, 259, 1926.

[3] H. Sponer, *Proceedings of the National Academy of Science*, **13**, 100, 1927, and *Zeitschrift für Physik*, **41**, 611, 1927.

[4] J. J. Hopfield, *Physical Review*, **27**, 801, 1926 (abstract 25).

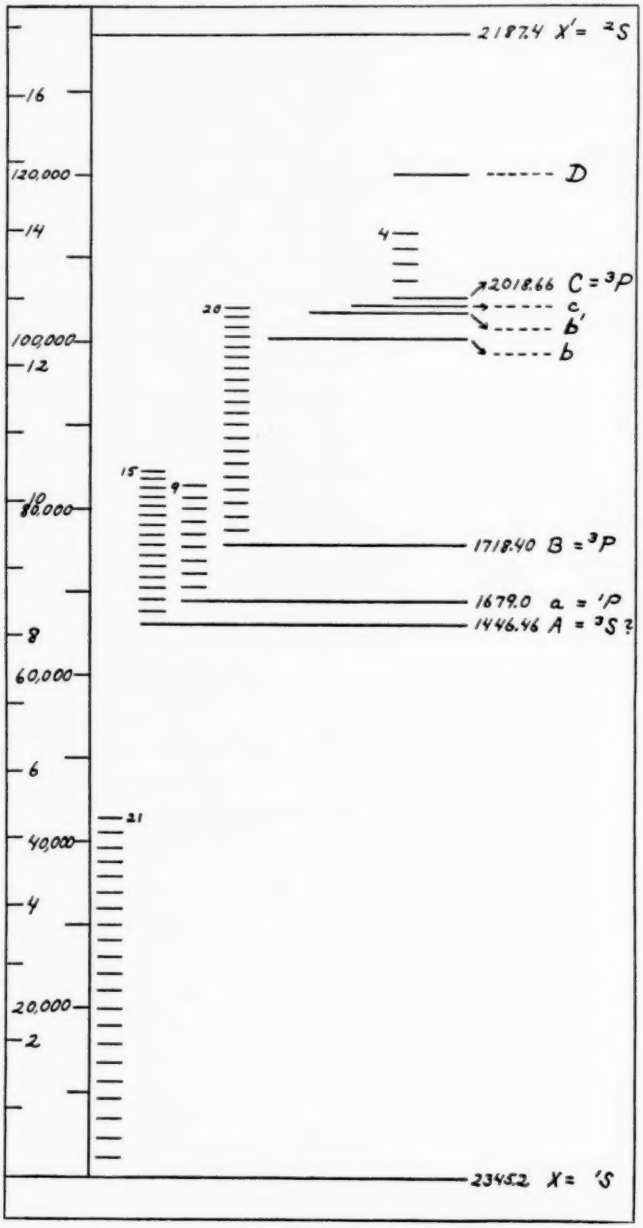


FIG. 2.—Energy levels of N_2

a to be one normal and one 2.39 volt excited atom, one obtains 11.85 volts as the normal heat of dissociation, in close agreement with the previous value. For level A we have electronic energy of 8.18 volts (using the revision established by Poetker),[1] and a limiting amount of vibrational energy of 3.70 volts, a total of 11.88 volts.[2] The total energy necessary for dissociation from states B and C, as given by Birge and Sponer, is 14.62 and 14.64 volts, respectively. These amounts are 0.4 volt higher than for state a, and are not easy to explain. The next higher level of the nitrogen atom is at 3.56 volts,[3] i.e., 1.17 volts above the 2.39-volt level. It is very probable that level X is a ^1S state, and that levels a, B, and C are P states (^1P, ^3P, and ^3P, respectively). It is also probable, but by no means certain, that level A is a ^3S state. Assuming that the S states give dissociation into two normal atoms, and the P states into one normal and one 2.39-volt excited atom, the calculated values of the normal heat of dissociation from states X, A, a, B, and C are 11.75, 11.88, 11.85, 12.23, and 12.25 volts, respectively. The most probable value is 11.9 volts.

One can, in contrast, assume that the dissociation from state A is into one normal and one 2.39-volt excited atom, giving a true heat of dissociation of about 9.5 volts. Such an assumption requires that dissociation from states a, B, and C give two 2.39-volt excited atoms, with a resulting discrepancy no larger than before. This second assumption agrees much better with the very recent data of Herzberg[4] on the heat of dissociation of N_2^+, which seems to show that this quantity can scarcely be greater than 7.1 volts and is probably slightly less. It agrees also with the Hogness and Lunn[5] value of 24 volts for the appearance of N^+ ions. Thus in the equation[6] $I_m+D'=D+I_a$, possible values under this second assumption are $16.9+7.1=9.5+14.5=24.0$ volts. This requires, however, that the linear

[1] *Ibid.*, **30**, 812, 1927.

[2] The older numbering of the A-state levels gives $8.00+\frac{1}{3}.88=11.88$ volts, as used by Birge and Sponer (*ibid.*, **28**, 259, 1926).

[3] Unpublished work by K. T. Compton and J. C. Boyce, kindly communicated by Professor Compton.

[4] G. Herzberg, *Annalen der Physik*, **86**, 189, 1928.

[5] T. R. Hogness and E. G. Lunn, *Physical Review*, **26**, 786, 1925.

[6] See Birge and Sponer, *loc. cit.*

extrapolation of the ω_n curve for the normal state of both N_2 and N_2^+ give a heat of dissociation some 2 volts too high. Considerable data on the exact shape of ω_n curves has now accumulated, and one of us intends to discuss this matter in a separate paper.

The great preponderance of evidence seems now to be tending toward the 9.5-volt value for the heat of dissociation of N_2, and we are inclined to accept it. For a more critical discussion of this question, the reader is referred to a very recent paper by R. S. Mulliken,[1] and to two communications in *Nature*,[2] by R. S. Mulliken and R. T. Birge, respectively.

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[1] R. S. Mulliken, *Physical Review*, November, 1928.

[2] *Nature*, in press.

STELLAR RADIATION MEASUREMENTS[1]

By EDISON PETTIT and SETH B. NICHOLSON

ABSTRACT

Construction and properties of thermocouples.—Thermocouples are made of wires of bismuth and bismuth-tin alloy, 0.03 mm in diameter, mounted in an evacuated cell provided with a rock-salt window. The image of Betelgeuse formed by the 100-inch telescope raises the temperature of the receiver 0°.015 C.; that of Boss 4342 gives an increase of 0°.000009 C.

Method and accuracy of measurement.—The deflections of the D'Arsonval galvanometer are registered photographically throughout. A water-cell 1 cm thick is used to separate the infra-red radiation. Table II shows the radiometric magnitudes and corresponding galvanometer deflections for the sensitivity ordinarily used. For this adjustment Altair gives a deflection of 49.4 mm. A discussion of the effects of air currents, bad seeing, sky radiation, and galvanometer steadiness shows that under good conditions the probable error of an observed deflection is ±0.01 or ±0.02 mm, and that stars of radiometric magnitudes +6 to +7 may be measured with an uncertainty of 0.1 mag.

Radiometric terms.—The "radiometric magnitude" of any star is defined as equal to the apparent magnitude of an A0 star which will give the observed galvanometer deflection. "Heat-index" is visual *minus* radiometric magnitude, and "water-cell absorption" is the fraction of radiation absorbed by the water-cell expressed in magnitudes.

Observational results.—The list of 124 stars thus far observed (Table III) has been reduced to a homogeneous system of radiometric magnitudes, heat-indices, and water-cell absorptions. The standard conditions adopted are: star in zenith at Mount Wilson; two reflections from fresh silver in the telescope; rock-salt window on the thermocouple. The correction to no atmosphere, total radiation reaching the solar system, and the computed bolometric magnitude are also given for each star. The temperatures and diameters computed from the radiometric results are given for stars of special interest.

Giants and dwarfs.—Both heat-index and water-cell absorption, when plotted against spectral type, show distinct branches between F5 and M0, the giants in this region showing greater values of both heat-index and water-cell absorption. This indicates a lower temperature for the giants than for the dwarfs.

Stars as black bodies.—The plot of heat-index against water-cell absorption shows that the red stars deviate from black-body conditions. The N-type stars radiate more like black bodies than the M stars having the same water-cell absorption.

Temperatures from heat-index and water-cell absorption.—For stars earlier than G5, the heat-index gives consistently higher temperatures than the water-cell, possibly because of the unknown visual sensibility-curve corresponding to the Harvard system, or because of unknown deviations of these stars from black-body radiators.

Radiation constant for the radiometric magnitude scale.—Comparison of stars with three different standards gives 17.3×10^{-12} cal cm^{-2} min^{-1} for the radiation received at the earth's surface on Mount Wilson from a star of zero radiometric magnitude in the zenith. The radiometric magnitude of the Hefner lamp is −20.00, and its water-cell absorption, 2.7 mag. The radiometric magnitude of the standard candle is −20.11, and its heat-index, 5.82 mag.

Bolometric magnitudes.—The scale of bolometric magnitudes is made to coincide with the radiometric magnitudes at G0, which differs from Eddington's scale by about 0.1 mag.

Diameters from radiometric data.—The diameters measured with the interferometer

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 369.

are about two-thirds as great as those computed from radiometric data. Since the stars thus far measured with the interferometer are of late spectral class, this difference is probably due to the fact that they are not black-body radiators.

Brightest stars.—Sirius is third in the list of radiometrically brightest stars, being preceded by Betelgeuse and Antares.

Spectroscopic binaries and close double stars.—As a class these stars show no abnormalities in water-cell absorption and heat-index.

Eclipsing variables.—Algol and λ Tauri have been studied. The range in radiometric magnitude is practically the same as that observed in violet light with the photoelectric cell. The variations in radiometric and visual magnitude seem to be synchronous. There is no evidence of increased water-cell absorption as minimum is reached.

Long-period variables.—The results from heat-curves for maximum and minimum are given for ten of these stars. The radiometric range is 0.9 mag., while the visual range is 5.1 mag. The range in water-cell absorption is 0.67 mag. The diameters of these stars average 0".025 at maximum and 0".022 at minimum. Their mean absolute bolometric magnitude of −3.1 corresponds to that of a Cepheid of about 10 days' period.

Cepheids.—δ Cephei and η Aquilae have a radiometric range of 0.45 mag., while the visual range is 0.8 mag. The heat-indices and water-cell absorptions show changes with phase. This indicates changes in spectral type which, for δ Cephei, are the same as those determined spectroscopically, but for η Aquilae are nearly a spectral division later. The temperatures at minimum are about 20 per cent lower than at maximum, and the diameters at maximum are about 30 per cent smaller than at minimum.

This paper discusses measurements of stellar radiation made during the period 1922 to 1927 with vacuum thermocouples attached to the 100-inch telescope. Twelve different thermocouples in cells provided with windows of rock salt, fluorite, quartz, and microscope cover-glass were employed. The methods of constructing thermocouples described in a previous paper[1] have been varied considerably since, in the meantime, wires of bismuth and of the alloy of bismuth with 5 per cent of tin have become available through the work of G. F. Taylor,[2] who developed the technique of drawing these metals in glass tubing, which is later removed with hydrofluoric acid.

The operations involved in producing thermocouples from these wires, which are about 0.03 mm in diameter, are carried out under a microscope with a binocular eyepiece, magnifying ×16 to ×50. The wires are placed on a turntable, surfaced with a plate of glass resting on a sheet of white paper. This serves as the microscope stage. A small spot on the glass is moistened with a saturated solution of $ZnCl_2$. The wires are laid on the spot with a speck of solder near the junction, and welded together with a nichrome wire loop heated to incandescence with an electric current. The $ZnCl_2$ is washed away with water and alcohol, and the plate glass is warmed over a flame.

[1] *Mt. Wilson Contr.*, No. 246; *Astrophysical Journal*, **56**, 295, 1922.

[2] *Physical Review*, **23**, 655, 1924.

The receiver is then formed by flattening the globule of metal at the junction with a plate of glass. For the smallest receivers the wires are welded without solder. Receivers larger than 0.7 mm are made of copper and soldered to the junctions, although in the case of thermopiles they are attached with white lead.

The receivers are blackened with a thin mixture of lampblack and platinum black in alcohol and turpentine, as previously described. The thermocouple is attached to the solder-covered lead wires by the use of $ZnCl_2$ flux, which is afterward removed with wet cotton on the point of a stick. The use of the binocular microscope greatly facilitates the operations, many of which are critical; for example, the application of the heater for a fraction of a second too long is fatal.

The weight of a compensated thermocouple with two electrically opposed junctions, provided with receivers half a millimeter in diameter, including connecting wires, is about 0.1 mg, or one-thousandth part of a drop of water. The mass of the receiver which is heated by the star is only 0.035 mg. From the electrical properties of the circuit it can be shown that a galvanometer deflection of 1 millimeter corresponds to a rise in temperature of 33-millionths of a degree Centigrade in the receiver. For the giant star Betelgeuse, which is radiometrically the brightest we have measured, the rise in temperature of the receiver is 15-thousandths of a degree; and for the radiometrically faint dwarf, Boss 4342, whose visual magnitude is 7.9, the rise is only 9-millionths of a degree.

METHOD OF OBSERVING

The method of measuring stellar radiation with the vacuum-thermocouple used throughout the series has already been described[1] and need be only summarized here. The thermocouple cell is clamped to the double-slide plateholder at the Newtonian focus of the 100-inch reflector.[2] A water-cell 1 cm thick is provided, which can be placed in the convergent beam from the 100-inch mirror. The thermocouple is connected by a cable with a Leeds and Northrup D'Arsonval galvanometer of current sensitivity 3×10^{-10} amp. per

[1] *Mt. Wilson Contr.*, No. 246; *Astrophysical Journal*, **56**, 295, 1922.

[2] *Popular Astronomy*, **32**, 601, 1924.

millimeter at 8 meters scale-distance. The deflections are registered on a moving photographic plate, 6 to 10 meters distant from the galvanometer. The star image is focused on the receivers by the method of optical parallax; and the deflections are produced by shifting the thermocouple with one of the guiding screws so that the image falls alternately on the two junctions at regular intervals of 20 seconds, as indicated by a buzzer operated by the motor-driven registering device.[1] The linear relationship of the deflections obtained with this apparatus to the intensity of the incident radiation has been already pointed out.[2]

Ordinarily eight deflections are registered in this manner, after which the water-cell is thrown into the convergent beam from the 100-inch mirror. After refocusing the telescope, another set of eight deflections, produced by the radiation transmitted by the water-cell, is registered. The deflections are measured on a specially adapted comparator[3] to hundredths of a millimeter. The water-cell is of brass tubing 2 cm in diameter, with microscope cover-glass windows 0.165 mm thick, separated 1 cm. These have been replaced only once. Ordinarily the cell was cleaned and refilled with distilled water before each two or three nights' observing. Transmission measurements and other tests convince us that a plate of crystal alum between quartz plates would be more permanent than the water-cell and give a sharper cutoff (at λ 1.45 μ);[4] but this was not available at the beginning of the observations, and it was thought best to complete the series with the water-cell.

REDUCTION OF THE MEASUREMENTS

To reduce measurements of stellar radiation made on different nights over a period of years to a homogeneous system, it is convenient to state the intensities in terms of radiometric magnitude, which we have defined[5] as the visual magnitude of an Ao star which would give the observed galvanometer deflection. Ao stars were chosen for the determination of the zero point since photographic

[1] *Journal of the Optical Society of America*, **10**, 267, 1925.

[2] *Ibid.* [3] *Ibid.*

[4] *Mt. Wilson Contr.*, No. 336; *Astrophysical Journal*, **66**, 43, 1927.

[5] *Publications of the Astronomical Society of the Pacific*, **34**, 181, 1922.

and visual magnitudes are equal for this spectral class; and, since heat-index is visual *minus* radiometric magnitude, the heat-index, like the color-index, is also zero for these stars. Table II shows the relation between radiometric magnitude and the average galvanometer deflection. All measurements were reduced to the following conditions, which we have adopted as standard: star in the zenith at Mount Wilson; two reflections from fresh silver in the telescope; and rock-salt window on the thermocouple. The reductions to these standard conditions will be discussed in order of their importance.

Reduction to the zenith.—The observing program for each night usually included two stars which were observed at three or more zenith distances covering the entire range in zenith distance for the rest of the stars on the list. One of these stars was observed before and the other after midnight. Since the zenith distances of these stars seldom exceeded 60°, the logarithms of their galvanometer deflections, plotted against secants of the zenith distances, are represented by a straight line. The change in the logarithm of the deflection for unit air mass may be read from these plots, and this quantity divided by 0.4 is the change, A, expressed in magnitudes. If we eliminate four values for nights of doubtful character, the values of A range from 0.07 to 0.49 mag., with a mean value of 0.165 mag. A special-series determination, based on stars of different spectral types, gave a mean of 0.16 mag., and showed little variation with spectral type.

The reduction to the zenith at Mount Wilson is

$$\Delta^1 m_r = -A \ (\sec Z - 1) ,$$

which is to be added to the radiometric magnitude observed at the zenith distance Z. For nights on which A was not determined, the mean value 0.16 mag. was used. The observing program was planned so that the stars would be measured as near the meridian as possible, thus making $\Delta^1 m_r$ a minimum. The average value of $\Delta^1 m_r$ was −0.05 mag., and in only about 6 per cent of the observations did it exceed −0.15 mag.

Aging of the silver.—As the program of measurements of stellar radiation progressed, it was noticed that the observed radiometric magnitudes of red stars were decreasing, and those of blue

stars increasing, with the time elapsed since the silvering of the Newtonian flat, which had been resilvered much less frequently than the 100-inch mirror. This was due to the relatively great decrease in the reflecting power of the mirror in the violet as the tarnish of the silver increased.

To determine the correction $\Delta^2 m_r$ necessary to reduce the observed radiometric magnitudes to fresh silver, measurements of stars of various spectral classes were made just before and just after silvering. Combined with the data obtainable from the series of routine measurements, these gave S, the daily change in the observed radiometric magnitudes due to the tarnishing of the silver,

TABLE I

Spectral Class	$S\times 10^6$ Mag.	$\Delta^1 m_r$ Mag.	$S'\times 10^6$ Mag.
Bo	−205	0.000	−150
Ao	0	0.000	−112
Fo	+ 57	−0.004	− 83
Go	+110	−0.018	− 61
Ko	+156	−0.032	− 49
Mo	+194	−0.046	− 41
M7e	+205	−0.056	− 33
Me min.	+205	−0.067	− 30

for stars of various spectral classes. The values of S are given in the second column of Table I. It is not to be inferred from the data of this table that there is no loss for Ao stars. The values here are relative and have been made zero for Ao, in order that the zero point of the scale of radiometric magnitudes would remain unchanged. The reduction to fresh silver is

$$\Delta^2 m_r = SD,$$

where D is the number of days elapsed since silvering.

The average value of $\Delta^2 m_r$ at the time this effect was discovered was about $\pm$0.08 mag., with a maximum of about 0.2 mag. for the extremes of spectral class; but afterward it did not exceed one-half these values.

Absorption by the window.—Since there is little energy in stellar radiation having wave-lengths exceeding 4 μ, the corrections for measurements made with a thin glass or quartz window on the

thermocouple-cell are small, and those for a fluorite window are negligible. The correction for thin glass and quartz is nearly the same, and was found for stars of different spectral classes by measuring the radiation transmitted through quartz and glass with a thermocouple having a rock-salt window, such as was used in most of the determinations. The third column of Table I gives the values of $\Delta^3 m_r$ which reduce radiometric magnitudes determined with cells having glass or quartz windows to values determined with cells having rock-salt windows.

The average correction from all causes, regardless of sign, was about 0.16 mag., but the algebraic mean was nearly zero.

Water-cell absorption.—The water-cell absorption, being the fraction of radiation absorbed by the cell, expressed in magnitudes, is also (four-tenths) the logarithm of the ratio of the galvanometer deflections observed before and after the cell is placed in the beam. It is, therefore, independent of the sensitivity of the electrical circuit. The corrections reducing water-cell absorptions to the zenith, which are differential, were found to be negligible for the range of zenith distance which obtained in practice.

The effect of tarnished telescope mirrors on the water-cell absorption of stellar radiation was determined in the same way as the similar effect on radiometric magnitudes. The rates, S', at which the stars of various spectral types are affected are given in the fourth column of Table I.

Since the absorption of thin glass and quartz is in the region of wave-lengths greater than 1.3 μ, the corrections which reduce the water-cell absorption obtained with cells having windows of these materials to values obtained with a cell having a rock-salt window are the same as those for radiometric magnitude, but with opposite sign, and were taken from the third column of Table I.

Conditions affecting accuracy of measurement.—The size of the deflections for a given radiometric magnitude varied somewhat with the different thermocouples, galvanometers, and scale-distances employed. The order of accuracy obtainable is indicated in Table II, which shows the deflections produced by stars of different radiometric magnitudes, based on a deflection of 49.4 mm for Altair. Deflections twice as large as these have been used on several oc-

casions, and on others, deflections only about half as large; the sensitivity indicated in Table II may, however, be regarded as about normal.

Since, with few exceptions, the radiometric magnitudes of the stars in the present list are brighter than 4.2, the deflections usually exceeded 2 mm. For some faint dwarfs and for a few red stars observed for special purposes, the radiometric magnitude reached 7, with deflections between 0.1 and 0.2 mm. Under good conditions of observing, these small deflections are perfectly definite and may be

TABLE II

Radiometric Magnitude m_r	Galvanometer Deflection
	mm
− 2	(631)
− 1	250.00
0	100.00
+ 1	39.80
+ 2	15.90
+ 3	6.30
+ 4	2.51
+ 5	1.00
+ 6	0.40
+ 7	0.16
+ 8	0.06
+ 9	0.02
+10	0.01

determined to an accuracy corresponding to about a tenth of a magnitude.

The accuracy of a single measurement depends on several circumstances. On a quiet mild night in summer or autumn, the lines of the galvanometer record are smooth; and such a plate gives a probable error of ±0.01 or ±0.02 mm. For values less than about 40 mm the uncertainty seems to be nearly independent of the size of the deflection. Under these circumstances we regard deflections of 4 or 5 mm as rather large, and measurements on stars of radiometric magnitude +6 or +7 will then yield good results. In winter and spring, when the temperature changes rapidly, and especially if a cold wind is blowing, the lines of the record are seldom smooth; and, under extreme conditions, the galvanometer may wander over several

millimeters, or even centimeters, thus making accurate measurements impossible.

The effects of bad seeing depend largely on the size of the receivers of the thermocouple. With receivers 0.8 mm in diameter, observations may be made at the 42-foot focus of the 100-inch telescope with seeing 1 on a scale of 10, provided the star image is not "blowing up"; but with receivers 0.3 to 0.4 mm in diameter, a distinct unsteadiness appears in the record when the seeing is less than 3.

Moonlight and sunlight in no way affect the measurements. The thermocouple is compensated against general radiation, and, since the measurements are differential, the stars give the same deflection in the daytime sky as at night. We have measured stellar and planetary radiation from objects within 11° of the sun, and, except for the generally bad seeing which prevails in the daylight sky, the results are the same as if these objects were measured at night.

One of the principal advantages of the photographic method is the feasibility of eliminating defective deflections and tracing to their sources the disturbances producing them. As already pointed out in another paper,[1] the galvanometer drift which makes its appearance in cold or windy weather is practically eliminated by our method of measuring the photographic record.

OBSERVATIONAL RESULTS

Table III gives for 124 stars the following data: (1) name of star; (2) right ascension, α 1925; (3) declination, δ 1925; (4) spectral type, Sp; (5) absolute visual magnitude, M_v; (6) Harvard visual magnitude, m_v; (7) apparent radiometric magnitude, m_r; (8) heat index, H.I.; (9) water-cell absorption, W.C.; (10) correction to no atmosphere, Δm_r, which includes atmospheric absorption and losses in the telescope; (11) total radiation in cal cm^{-2} min^{-1} incident outside the earth's atmosphere, $E \times 10^{12}$; (12) absolute bolometric magnitude, M_B; (13) absolute temperatures Centigrade, T, from the heat-index and water-cell absorption; (14) apparent diameters, d, calculated from these data; and (15) number of observations. The stars are arranged in order of spectral class, and, within each spectral division, according to right ascension. The spectral classi-

[1] *Journal of the Optical Society of America*, **10**, 267, 1925.

TABLE III

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Star	α 1925	δ 1925	Sp.	M_V	m_V	m_r	H.I.	W. C.	Δm_r	$E\times10^{12}$ cal.	M_B	T	d	No.
ι Orionis*	5^h31^m8	$-5°57'$	O9n	−3.6	2.87	2.79	+0.08	0.19	2.94	20.0	−5.7	25000°	0.00032	7
ζ Orionis*	5 37.0	−1 59	.....	.....	1.91	1.94	−0.03	0.24	.....	34.7	.....	.....	.....	2
ζ Orionis A	5 37.0	−1 59	B0n	−4.0	2.05	2.08	.....	.....	2.72	31.2	−5.8	.....	.....	.....
ζ Orionis B	5 37.0	−1 59	B1n	−1.9	4.21	4.24	.....	.....	2.51	3.5	−3.5	.....	.....	.....
δ Orionis*	5 28.2	−0 21	B1n	−4.0	2.48	2.29	+0.19	0.24	2.51	21.1	−5.8	.....	.....	3
ϵ Orionis	5 32.4	−1 15	B1n	−4.7	1.75	1.69	+0.06	0.21	2.51	36.9	−6.4	.....	.....	7
κ Orionis	5 44.2	−9 42	B1n	−3.9	2.20	2.20	0.00	0.25	2.51	23.1	−5.5	.....	.....	2
γ Pegasi	0 9.4	+14 46	B2	.....	2.87	2.91	−0.04	0.17	2.31	9.9	.....	.....	.....	2
γ Orionis	5 21.1	+6 17	B2s	−3.5	1.70	1.66	+0.04	0.21	2.31	31.4	−6.0	.....	.....	7
o Persei*	3 39.7	+32 3	B3	−0.8	3.94	3.74	+0.20	0.20	2.12	3.9	−2.2	.....	.....	2
λ Tauri M*	3 56.5	+12 17	B3	−3.1	3.38	3.33	+0.05	0.26	2.12	5.5	−4.4	.....	.....	c
Spica*	13 21.2	−10 46	B3n	−1.7	1.21	1.00	+0.21	0.18	2.12	48.5	.....	.....	.....	20
Spica A	13 21.2	−10 46	B3n	−1.0	1.96	1.75	.....	.....	2.12	24.2	−2.4	17000	0.00078	.....
Spica B	13 21.2	−10 46	B3n	−1.0	1.96	1.75	.....	.....	2.12	24.2	−2.4	17000	0.00078	.....
η Ursa Maj	13 44.6	+49 41	B3	−3.5	1.91	1.96	−0.05	0.20	2.12	20.0	−4.8	.....	.....	3
Algol M*	3 3.3	+40 40	B8	−0.1	2.05	2.18	−0.13	0.23	1.39	8.4	−0.5	13000	0.00076	c
Algol m*	3 3.3	+40 40	.....	.....	3.27	3.40	−0.13	0.23	1.39	2.7	.....	.....	.....	c
η Tauri	3 43.0	+23 52	B8n	−2.0	2.96	2.98	−0.02	0.27	1.39	4.1	−2.5	.....	.....	7
Rigel*	5 10.9	−8 17	B8p	−5.5	0.34	0.23	+0.11	0.23	1.39	50.4	−6.1	13000	0.0017	8
27 Tauri	3 44.8	+23 50	B9n	−1.2	3.80	3.67	+0.13	0.34	1.28	1.9	−1.7	.....	.....	1
β Tauri	5 21.5	+28 33	B9s	−0.9	1.78	1.74	+0.04	0.30	1.28	11.4	−1.3	.....	.....	3
Regulus	10 4.4	+12 20	B9n	+0.5	1.34	1.47	−0.13	0.25	1.28	14.4	+0.2	12500	0.0013	28
α Pegasi*	23 1.0	+14 48	B9n	+0.2	2.57	2.67	−0.10	0.23	1.28	4.4	−0.1	.....	.....	3
α Andromedae*	0 4.5	+28 41	A0n	+1.1	2.15	2.15	0.00	0.35	1.19	7.2	+0.8	.....	.....	3
α Corona Bor.*	15 32.5	+26 58	A0n	+1.1	2.31	2.38	−0.07	0.21	1.19	5.7	+0.9	.....	.....	2
Vega	18 34.4	+38 43	A1s	+0.7	0.14	0.10	+0.04	0.26	1.11	43.9	+0.4	10600	0.0028	37
Sirius	6 41.8	−16 37	A2s	+1.2	−1.58	−1.27	−0.31	0.25	1.04	145.2	+1.4	10100	0.0053	7
Castor*	7 29.8	+32 3	.....	.....	1.58	1.74	−0.16	0.27	.....	8.4	.....	.....	.....	3
Castor A*	7 29.8	+32 3	A2s	+1.1	1.99	2.16	.....	.....	1.04	6.1	+1.1	10100	0.0011	.....
Castor B*	7 29.8	+32 3	A6s	+2.0	2.85	2.99	.....	.....	0.82	2.3	+2.2	8200	0.0010	.....
β Ursae Maj	10 57.3	+56 47	A2s	+0.6	2.44	2.51	−0.07	0.23	1.04	4.4	+0.6	.....	.....	2
ζ^1 Ursae Maj*	13 20.9	+55 19	A2s	+0.7	2.40	2.39	+0.01	0.20	1.04	4.9	+0.5	.....	.....	2
Altair	19 47.1	+8 40	A2n	+2.5	0.89	0.74	+0.15	0.30	1.04	22.8	+2.2	10100	0.0021	48
α Cygni	20 38.9	+45 1	A2p	−5.2	1.33	1.24	+0.09	0.31	1.04	14.3	−5.4	10100	0.0017	10
γ Boötis	14 29.1	+38 38	A3n	+2.0	3.00	3.06	−0.06	0.24	0.98	2.6	+2.0	.....	.....	1
Fomalhaut	22 53.5	−30 1	A3	+2.0	1.29	1.38	−0.09	0.37	0.98	12.1	+2.0	10000	0.0020	3
δ Aquilae	19 21.7	+2 58	A4n	+2.3	3.44	3.27	+0.17	0.41	0.92	2.0	+2.1	.....	.....	4
η Aquilae M	19 48.7	+0 49	F0	−2.2	3.66	3.22	+0.44	0.49	0.41	1.3	−2.2	4950	0.0021	c
η Aquilae m	19 48.7	+0 49	G1	−1.4	4.45	3.65	+0.80	0.75	0.42	0.9	−1.7	3900	0.0028	c
δ Cephei M	22 26.4	+58 2	F1	−2.3	3.68	3.40	+0.28	0.34	0.52	1.2	−2.2	6200	0.0013	c
δ Cephei m	22 26.4	+58 2	G0	−1.5	4.44	3.87	+0.57	0.55	0.40	0.7	−1.6	4580	0.0018	c

TABLE III—*Continued*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Star	α 1925	δ 1925	Sp.	M_V	m_V	m_r	H.I.	W. C.	Δm_r	$E\times10^{12}$ cal.	M_B	T	d	No.
β Cassiopeiae	$0^h\ 5^m.2$	+58°44′	F2	+ 1.6	2.42	2.25	+0.17	0.38	0.52	3.6	+1.8	.....	.....	1
α Trianguli*	1 48.8	+29 13	F2	+ 1.9	3.58	3.26	+0.32	0.38	0.48	1.3	+2.0	.....	.....	3
Procyon	7 35.4	+ 5 25	F3	+ 2.9	0.48	0.22	+0.26	0.43	0.46	21.5	+3.1	5620°	0.0067	6
α Persei	3 19.0	+49 36	F5	− 2.4	1.90	1.62	+0.28	0.41	0.46	5.9	−2.2	5650	0.0035	7
ξ Pegasi	22 44.0	+11 54	F5	+ 3.2	4.31	3.91	+0.40	0.56	0.42	0.7	+3.3	.....	.....	1
η Boötis*	13 51.1	+18 46	F9	+ 2.8	2.80	2.48	+0.32	0.47	0.44	2.7	+2.9	.....	.....	5
ϵ Leonis	9 41.6	+24 7	G0	− 2.3	3.12	2.64	+0.48	0.49	0.40	2.3	−2.4	.....	.....	3
β Canum Venat	12 30.2	+41 46	G0	+ 4.4	4.32	3.90	+0.42	0.40	0.44	1.6	+4.5	.....	.....	2
λ Serpentis	15 42.8	+ 7 35	G0	+ 4.3	4.42	4.15	+0.27	0.44	0.46	0.6	+4.5	5560	0.0011	2
γ Cygni	20 19.5	+40 1	G0p	− 5.4	2.32	1.94	+0.38	0.43	0.40	4.2	−5.3	5350	0.0032	3
α Aquarii	22 1.9	− 0 41	G0	− 2.3	3.19	2.49	+0.70	0.53	0.40	2.6	−2.5	4460	0.0036	4
Sun	.....	.....	G0	+ 4.8	−26.72	−27.18	+0.46	0.41	0.45	1.93×10^{12}	+4.8	5450	.....	.....
ι Persei	3 3.4	+49 20	G1	+ 4.1	4.17	3.91	+0.26	0.45	0.46	1.6	+4.3	.....	.....	1
Capella*	5 11.1	+45 55	G0	.....	0.21	− 0.38	+0.59	0.52	.....	35.9	.....	.....	.....	12
Capella A	5 11.1	+45 55	G1	− 0.3	0.74	0.07	+0.67	0.57	0.40	23.4	−0.4	4390	0.011	.....
Capella B	5 11.1	+45 55	F5	+ 0.2	1.24	0.78	+0.46	0.44	0.43	12.5	+0.2	5120	0.0061	.....
β Comae	13 8.4	+28 16	G1	+ 5.0	4.32	4.18	+0.14	0.44	0.50	0.6	+5.3	.....	.....	2
η Pegasi*	22 39.5	+29 50	G1	− 2.4	3.10	2.39	+0.71	0.58	0.40	2.8	−2.6	.....	.....	2
η Piscium	1 27.5	+14 58	G5	0.0	3.72	3.20	+0.52	0.57	0.40	1.3	0.0	.....	.....	2
β Herculis*	16 27.0	+21 39	G5	− 0.2	2.81	2.07	+0.74	0.65	0.40	3.8	−0.4	.....	.....	2
β Ceti	0 39.8	−18 24	G6	+ 0.3	2.24	1.48	+0.76	0.62	0.40	6.3	+0.1	4170	0.0066	12
ϵ Virginis	12 58.4	+11 22	G6	0.0	2.95	2.34	+0.61	0.69	0.41	2.9	−0.2	.....	.....	2
τ Ceti	1 40.6	−16 20	G7	+ 6.2	3.65	3.22	+0.43	0.51	0.41	1.3	+6.2	.....	.....	2
o Tauri	3 20.8	+ 8 46	G7	− 0.3	3.80	3.17	+0.63	0.55	0.40	1.3	−0.4	.....	.....	3
γ Tauri	4 15.5	+15 27	G7	+ 0.7	3.86	3.20	+0.66	0.58	0.40	1.3	+0.5	.....	.....	4
α Ursae Maj	10 59.1	+62 9	G8	− 0.4	1.95	1.11	+0.84	0.70	0.41	9.1	−0.8	3950	0.0088	2
ϵ Boötis*	14 41.7	+27 23	.....	.....	2.59	1.80	+0.79	0.72	.....	5.1	.....	.....	.....	4
ϵ Boötis A	14 41.7	+27 23	G8	− 0.9	2.70	1.85	+0.85	0.75	0.42	4.6	−1.3	.....	.....	.....
ϵ Boötis B	14 41.7	+27 23	A1	+ 1.5	5.12	5.06	+0.06	0.34	1.11	0.5	+1.2	.....	.....	.....
β Aquilae	19 51.6	+ 6 13	G8	+ 3.3	3.90	3.32	+0.58	0.52	0.40	1.2	+3.2	.....	.....	5
δ Eridani	3 39.7	−10 1	G9	+ 4.0	3.72	3.03	+0.69	0.64	0.40	1.5	+3.8	.....	.....	5
Pollux	7 40.7	+28 12	G9	+ 1.6	1.21	0.53	+0.68	0.62	0.40	19.6	+1.5	4260	0.0098	5
40 Eridani	4 11.7	− 7 46	K0	+ 6.0	4.48	4.01	+0.47	0.50	0.40	0.6	+6.1	4880	0.0015	6
ψ Ursae Maj	11 5.5	+44 54	K0	+ 1.3	3.15	2.27	+0.88	0.70	0.42	3.1	+0.9	.....	.....	2
Arcturus	14 12.2	+19 34	K0	+ 0.3	0.24	− 0.98	+1.22	0.80	0.44	64.0	−0.4	3520	0.029	16
τ Piscium	1 7.5	+29 42	K1	+ 0.5	4.70	3.96	+0.74	0.54	0.40	0.6	+0.2	.....	.....	5
α Arietis	2 2.9	+23 6	K1	+ 0.3	2.23	1.24	+0.99	0.72	0.42	8.1	−0.2	3780	0.009	30
ϵ Eridani	3 29.4	− 9 43	K1	+ 6.1	3.81	3.32	+0.49	0.58	0.40	1.2	+6.1	.....	.....	5
70 Ophiuchi*	18 1.7	+ 2 31	.....	.....	4.07	3.64	+0.43	0.63	.....	0.9	.....	.....	.....	5
70 Ophiuchi A	18 1.7	+ 2 31	K1	+ 5.7	4.28	3.95	+0.33	0.59	0.42	0.7	+5.9	5080	0.0014	.....
70 Ophiuchi B	18 1.7	+ 2 31	K5	+ 7.4	5.98	5.17	+0.81	0.76	0.42	0.2	+7.0	3860	0.0014	.....

TABLE III—*Continued*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Star	α 1925	δ 1925	Sp.	M_V	m_V	m_r	H.I.	W. C.	Δm_r	$E\times10^{12}$ cal.	M_B	T	d	No.
γ^1 Andromedae	$1^h59^m.3$	+41°58′	K2	− 2.3	2.28	1.20	+1.08	.0.90	0.44	8.6	−2.9	3480°	0.″010	1
α Serpentis	15 40.6	+ 6 40	K2	+ 0.8	2.75	1.95	+0.80	0.65	0.43	4.2	+0.5	.....	.....	5
δ Andromedae	0 35.3	+30 27	K3	+ 1.0	3.49	2.35	+1.14	0.72	0.42	3.0	+0.3	.....	.....	2
53 Eridani*	4 34.7	−14 27	K3	+ 2.2	3.98	3.22	+0.76	0.62	0.40	1.3	+1.9	.....	.....	5
β Cancri	8 12.4	+ 9 25	K4	− 1.5	3.76	2.30	+1.46	0.88	0.46	3.2	−2.5	.....	.....	14
α Hydrae	9 23.9	− 8 20	K4	− 2.1	2.16	0.88	+1.28	0.90	0.44	11.6	−2.9	3360	0.014	4
ξ Cephei	22 8.2	+57 50	K4	+ 0.6	3.62	2.24	+1.38	0.82	0.44	3.4	−0.3	.....	.....	23
Aldebaran	4 31.6	+16 22	K5	− 0.4	1.06	− 0.60	+1.66	0.96	0.46	46.0	−1.7	3120	0.032	19
γ Draconis	17 54.9	+51 30	K5	− 1.0	2.42	0.94	+1.48	1.00	0.46	11.1	−2.0	3160	0.015	1
ξ Cygni*	21 2.2	+43 38	K5	− 1.6	3.92	2.18	+1.74	1.04	0.48	3.7	−2.9	.....	.....	2
61^1 Cygni	21 3.5	+38 23	K5	+ 7.9	5.57	4.29	+1.28	0.70	0.42	0.5	+7.1	3635	0.0023	7
β Andromedae	1 5.5	+35 13	Mo	+ 0.6	2.37	0.45	+1.92	1.00	0.48	17.8	−0.9	3000	0.021	3
Cin. 1218	10 6.8	+49 51	Mo	+ 8.2	6.82	5.38	+1.44	1.06	0.50	0.2	+7.2	.....	.....	2
Boss 4342	17 1.2	− 4 57	Mo	+ 8.1	7.9	6.44	+1.5	1.03	0.43	0.1	+7.1	.....	.....	2
61^2 Cygni	21 3.6	+38 22	Mo	+ 8.6	6.28	4.86	+1.42	0.82	0.45	0.3	+7.7	3380	0.0023	7
Antares*	16 24.8	−26 16	M1	− 2.1	1.22	− 1.32	+2.54	1.21	0.54	95.9	−4.3	2660	0.063	6
Cin. 25	0 14.0	+43 36	M2	+10.3	8.1	5.9	+2.2	.....	0.51	0.1	+8.5	.....	.....	1
α Ceti	2 58.4	+ 3 48	M2	− 0.8	2.82	0.72	+2.10	1.05	0.49	13.9	−2.5	2880	0.020	18
Betelgeuse	5 51.1	+ 7 24	M2	− 3.1	0.92	− 1.67	+2.59	1.19	0.54	132.4	−5.3	2640	0.075	9
π Leonis	9 56.3	+ 8 24	M2	− 0.1	4.89	3.02	+1.87	1.26	0.52	1.7	−1.6	.....	.....	3
Boss 2935	10 59.3	+36 28	M2	+10.6	7.6	5.36	+2.2	1.04	0.46	0.2	+8.8	.....	.....	2
m Virginis	13 37.7	− 8 20	M2	+ 0.2	5.16	3.05	+2.11	1.21	0.52	1.7	−1.6	.....	.....	1
λ Aquarii	22 48.7	− 7 59	M2	0.0	3.84	1.82	+2.02	1.14	0.50	5.1	−1.6	.....	.....	2
β Pegasi*	23 0.1	+27 41	M2	− 0.6	2.61	0.27	+2.34	1.18	0.52	21.8	−2.5	2710	0.029	6
55 Pegasi	23 3.2	+ 9 0	M2	− 0.8	4.69	2.98	+1.71	0.99	0.48	1.7	−2.1	.....	.....	3
15 Trianguli	2 31.2	+34 22	M3	+ 0.1	5.62	3.40	+2.22	1.10	0.50	1.2	−1.7	.....	.....	20
η Geminorum	6 10.4	+22 32	M3	− 0.3	3.8	1.20	+2.6	1.20	0.54	9.4	−2.5	2700	0.019	3
μ Geminorum	6 18.4	+22 33	M3	− 0.2	3.19	0.67	+2.52	1.12	0.55	15.5	−2.4	2800	0.023	5
δ Virginis	12 51.8	+ 3 48	M3	− 0.2	3.66	1.22	+2.44	1.18	0.53	9.2	−2.3	2700	0.019	8
30 Piscium	23 58.1	− 6 26	M3	− 0.5	4.66	2.02	+2.64	1.28	0.55	4.4	−2.9	.....	.....	3
ρ Persei	3 0.4	+38 33	M4	+ 0.5	3.7	0.69	+3.0	1.29	0.58	15.7	−2.2	2550	0.028	4
51 Geminorum	7 9.1	+16 17	M4	− 0.2	5.31	2.35	+2.96	1.37	0.58	3.5	−2.8	.....	.....	1
Boss 3100	11 44.9	−26 20	M4	− 0.3	5.45	2.22	+3.23	1.20	0.57	3.8	−3.3	.....	.....	2
13 Sagittae	19 56.7	+17 19	M4	− 0.4	5.56	2.78	+2.78	1.27	0.56	2.3	−3.0	.....	.....	4
62 Sagittarii	19 58.0	−27 55	M4	0.0	4.60	1.68	+2.92	1.21	0.56	6.1	−2.6	.....	.....	3
R Trianguli M	2 32.5	+33 56	M5e	− 0.2	6.3	3.4	+2.9	1.2	0.53	1.2	−2.7	.....	.....	c
56 Leonis	10 52.1	+ 6 35	M5	− 0.6	6.05	1.87	+4.18	1.46	0.60	5.4	−4.3	2400	0.018	3
α Herculis*	17 11.2	+14 28	.....	.....	3.31	− 0.77	+4.08	1.50	.....	61.4	.....	.....	.....	14
α Herculis A	17 11.2	+14 28	M5	− 2.0	3.48	− 0.76	+4.24	1.51	0.61	61.1	−6.0	2340	0.065	.....
α Herculis B*	17 11.2	+14 28	F9	− 0.1	5.39	4.94	+0.45	.....	0.42	0.3	−0.1	.....	.....	.....

TABLE III—*Continued*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Star	α 1925	δ 1925	Sp.	M_V	m_v	m_r	H.I.	W. C.	Δm_r	$E\times10^{12}$ cal.	M_B	T	d	No.
R Lyrae	18^h53^m1	+43°51′	M5	− 0.6	4.32	0.62	+3.70	1.45	0.60	17.0	−4.1	2400°	0.033	21
o Ceti M*	2 15.6	− 3 19	.....	.....	3.6	− 0.2	+3.8	1.3	.....	34.8	.....	.....	.....	c
o Ceti A M	2 15.6	− 3 19	M6e	+ 0.1	3.6	− 0.2	+3.8	1.3	0.56	34.8	−3.4	2540	0.042	.....
o Ceti B	2 15.6	− 3 19	B8	+ 6.8	10.3	10.3	.....	.....	1.39	0.0	+6.3	.....	.....	.....
45 Arietis	2 51.6	+18 2	M6	+ 1.5	5.94	1.72	+4.22	1.46	0.60	6.1	−2.4	2390	0.020	5
X Ophiuchi M*	18 34.8	+ 8 43	.....	.....	6.5	1.6	+4.9	1.6	.....	7.1	.....	.....	.....	c
X Ophiuchi A M	18 34.8	+ 8 43	M6e	− 0.2	6.6	1.6	+5.0	1.6	0.63	7.1	−4.9	2260	0.024	.....
X Ophiuchi B	18 34.8	+ 8 43	Ko	+ 2.3	9.1	8.2	.....	.....	.....	0.0	.....	.....	.....	.....
χ Cygni M	19 47.7	+32 43	M6e	− 0.3	5.2	0.4	+4.8	1.6	0.63	17.0	−4.8	2260	0.041	c
R Cancri M	8 12.4	+11 58	M7e	− 0.4	6.6	1.9	+4.7	1.4	0.58	5.1	−4.8	2450	0.017	c
R Aquilae M	19 2.8	+ 8 7	M7e	0.0	6.1	1.8	+4.3	1.5	0.61	5.8	−4.0	2360	0.020	c
R Aquarii M*	23 40.0	−15 42	.....	.....	6.0	1.9	+4.1	1.7	.....	5.5	.....	.....	.....	c
R Aquarii A M	23 40.0	−15 42	M7e	− 1.6	6.0	1.9	4.1	1.7	0.65	5.5	−5.4	2180	0.022	.....
R Aquarii B	23 40.0	−15 42	B	+ 2.4	10.0	10.0	.....	.....	.....	0.0	.....	.....	.....	.....
R Leo Minoris M	9 41.1	+34 52	M8e	0.0	7.0	2.1	+4.9	1.6	0.63	5.6	−4.6	2260	0.019	c
R Leonis M	9 43.5	+11 47	M8e	+ 0.6	5.9	0.1	+5.8	1.6	0.63	28.3	−4.8	2260	0.047	c
R Hydrae M	13 25.6	−22 54	M8e	− 0.2	4.2	0.0	+4.2	1.5	0.61	30.4	−4.1	2360	0.045	c
R Trianguli m	2 32.5	+33 56	.....	− 5.5	12.0	4.3	+7.7	2.0	0.72	0.5	−2.0	1950	0.0096	c
o Ceti m*	2 15.6	− 3 19	.....	+ 5.5	9.0	0.7	+8.3	1.9	.....	17.3	.....	.....	.....	c
o Ceti A m	2 15.6	− 3 19	.....	+ 5.8	9.3	0.7	+8.6	1.9	0.70	17.3	−2.6	2020	0.046	.....
o Ceti B	2 15.6	− 3 19	B8	+ 6.8	10.3	10.3	.....	.....	1.39	0.0	+6.3	.....	.....	.....
X Ophiuchi m*	18 34.8	+ 8 43	.....	.....	8.9	2.3	+8.7	2.1	.....	4.2	.....	.....	.....	c
X Ophiuchi A m	18 34.8	+ 8 43	.....	+ 4.2	11.0	2.3	+8.7	2.1	0.75	4.2	−4.4	1890	0.026	.....
X Ophiuchi B	18 34.8	+ 8 43	Ko	+ 2.3	9.1	8.2	.....	.....	.....	0.0	.....	.....	.....	.....
χ Cygni m	19 47.7	+32 43	.....	+ 7.8	13.3	1.6	+11.7	2.7	0.88	8.9	−3.9	1580	0.057	c
R Cancri m	8 12.4	+11 58	.....	+ 4.4	11.4	2.8	+8.6	2.1	0.75	2.6	−4.1	1890	0.021	c
R Aquilae m	19 2.8	+ 8 7	.....	+ 5.5	11.6	2.7	+8.9	2.1	0.75	2.9	−3.2	1890	0.022	c
R Aquarii m*	23 40.0	−15 42	.....	.....	10.0	2.6	+7.4	2.3	.....	3.3	.....	.....	.....	c
R Aquarii A m	23 40.0	−15 42	.....	+ 5.2	12.8	2.6	10.2	2.3	0.80	3.3	−4.9	1760	0.027	.....
R Aquarii B	23 40.0	−15 42	B	+ 2.4	10.0	10.0	.....	.....	.....	0.0	.....	.....	.....	.....
R Leo Minoris m	9 41.1	+34 52	.....	+ 5.4	12.4	3.0	+9.4	2.2	0.77	2.3	−3.9	1830	0.020	c
R Leonis m	9 43.5	+11 47	.....	+ 4.9	10.2	0.9	+9.3	2.3	0.80	15.8	−4.2	1760	0.022	c
R Hydrae m	13 25.6	−22 54	.....	+ 4.8	9.3	1.0	+8.3	2.0	0.72	13.4	−3.2	1950	0.044	c
19 Piscium	23 42.6	+ 3 4	No	.....	5.3	2.1	+3.2	1.5	0.60	4.4	.....	2360	0.018	4
U Hydrae	10 33.8	−13 0	N2	.....	5.4	2.2	+3.2	1.5	0.62	3.9	.....	2360	0.016	13
X Cancri	8 51.2	+17 32	N3	.....	6.4	3.2	+3.2	1.6	0.63	1.6	.....	2260	0.011	10
VX Andromedae	0 15.9	+44 17	N7	.....	8.8	4.2	+4.6	1.8	0.69	0.7	.....	2010	0.009	7

* Spectroscopic binary or close double star. When data on the magnitudes and spectra of the components exist, their radiometric constants have been computed from curves in Figures 1 and 2. When the companion in a binary does not fall on the receiver, as for example in the case of Sirius, the asterisk has been omitted.

M = Maximum radiation (and light).

m = Minimum radiation (and light).

c = Radiometric magnitude and water-cell absorption read from curves of plotted observations.

fications are those of the Mount Wilson observers.[1] The classifications of K-type stars are from unpublished revised values. The absolute visual magnitudes were obtained by combining the Harvard visual magnitudes[2] in column 6 with unpublished parallaxes derived by van Maanen from a consideration of the available data from all sources, the only exceptions being the B stars, for which Kapteyn's

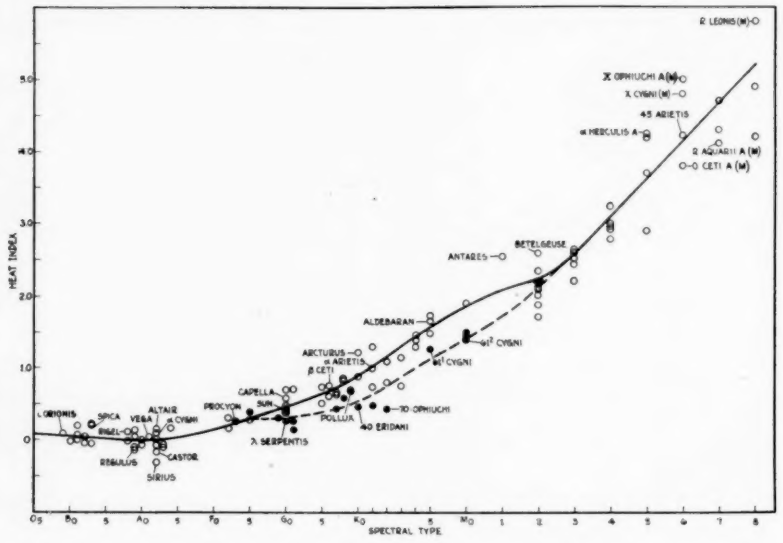

FIG. 1

group parallaxes were used when available, and the Pleiades stars, for which Trumpler's cluster parallax was used.

Figures 1 and 2 are plots of the heat-indices and water-cell absorptions, respectively, against spectral class. The giants are indicated by open circles, the heavy line being the mean values. The dwarfs are indicated by closed circles, the mean being shown by a dotted line. These plots show that the heat-index and water-cell absorption are greater for giants than for dwarfs of the same spectral class, which is in harmony with a similar relation already pointed

[1] *Mt. Wilson Contr.*, Nos. 199, 244, 262, 264, 319; *Astrophysical Journal*, **53**, 13, 1921; **56**, 242, 1922; **57**, 294, 1923; **58**, 215, 1923; **64**, 225, 1926.

[2] *Harvard Annals*, **50**, 1908.

out by Seares[1] and others for the color-index, and indicates a higher temperature for the dwarfs than for the giants of the same spectral type.

The crosses in the plot of water-cell absorptions in Figure 2 indicate observations by Coblentz[2] made with the 40-inch reflector at the Lowell Observatory. These observations, which are all of giant stars, are in good agreement with our curve.

In Figure 3 the heat-indices of the stars in Table III are plotted

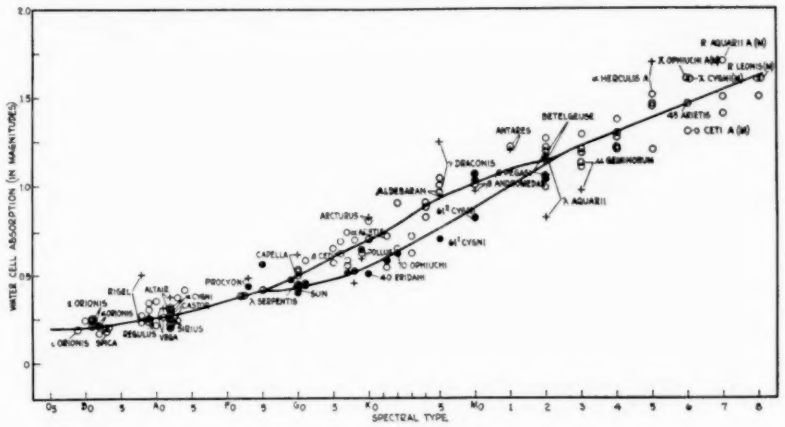

FIG. 2

against their water-cell absorptions, the full line representing the mean for these stars. The broken line is a plot of the water-cell absorptions and heat-indices given in Table IV, which have been calculated for black bodies at various temperatures on the basis of λ 0.555 μ as the maximum of visual sensibility; the dotted line is a similar curve derived with λ 0.529 μ instead of λ 0.555 μ. The scale of black-body temperatures is shown along with that of water-cell absorption.

The deviation of the curve observed for the stars of spectral classes later than M2 from that corresponding to black-body radiation indicates that stars of low temperature do not radiate like

[1] *Mt. Wilson Contr.*, No. 226; *Astrophysical Journal*, **55**, 165, 1922.

[2] *Scientific Papers of the Bureau of Standards*, **17**, 725 (No. 438), 1922; *Astrophysical Journal*, **55**, 20, 1922.

black bodies. Some of the deviations of individual stars from the mean curve may represent the effect of errors of observation, but in most cases they must be due to peculiarities of these bodies. It is interesting to note that the long-period variables at minimum

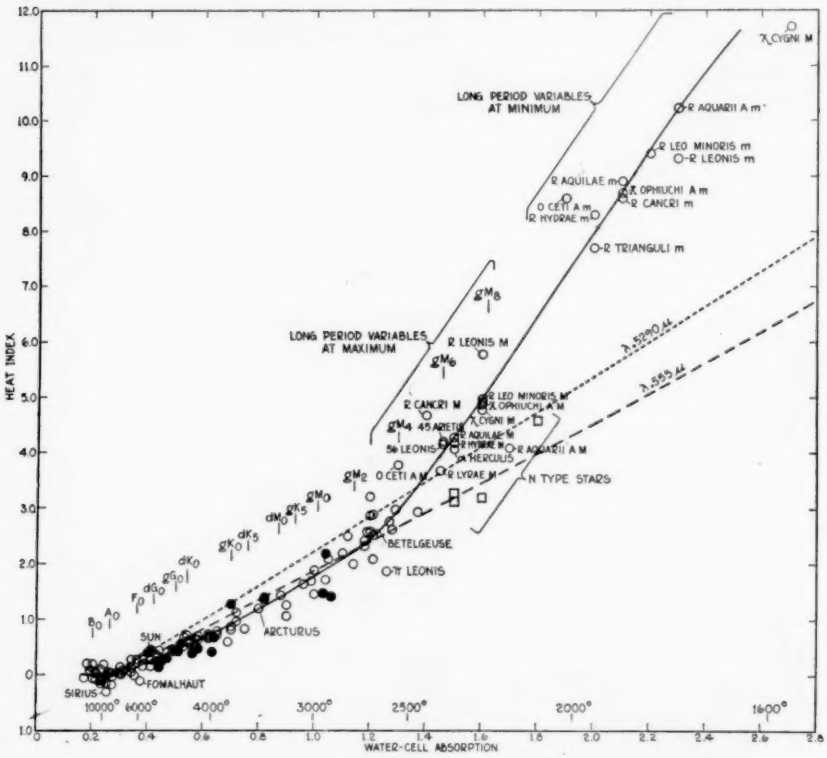

FIG. 3

fall on the extended curve of these stars at maximum, and deviate most widely from black-body radiators.

The four N-type stars, which are indicated on the plot by squares, apparently radiate more like black bodies than do the M-type stars having the same water-cell absorption.

TEMPERATURES FROM THE HEAT-INDEX AND WATER-CELL ABSORPTION

To determine temperatures from the heat-index, two factors which are affected by a much larger uncertainty than could be de-

sired must be decided upon, viz., the atmospheric absorption and the spectral sensibility-curve of the eye corresponding to the Harvard system of magnitudes. In determining temperatures from water-cell absorptions, on the other hand, the transmission curve of the water-cell,[1] which has been well determined, is substituted for the sensibility-curve of the eye. The water-cell absorptions are homogeneous material, independent of physiological effects, while the heat-indices are influenced by any magnitude and color errors affecting the Harvard system.

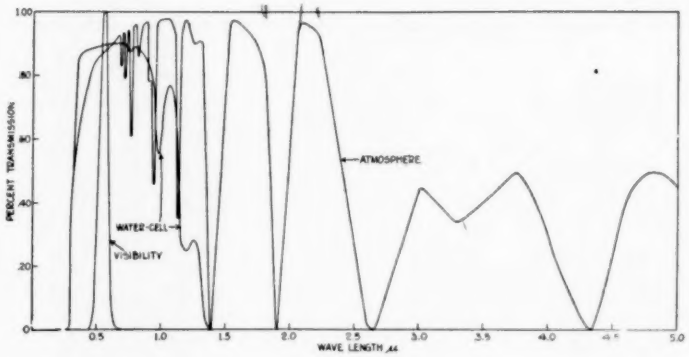

FIG. 4

For stars having very high temperatures—classes O, B, and A—the rate of change of both water-cell absorption and heat-index is so small that neither gives very reliable temperatures; but the heat-index probably gives the more trustworthy results. For low-temperature stars—class M—the temperatures derived by both methods are affected by the presence of titanium-oxide absorption bands which change the distribution of spectral energy from that of a black body; but the results from the heat-index are probably influenced more than those from the water-cell absorption.

Figure 4 gives the transmission-curves of the atmosphere and water-cell and the sensibility-curve of the eye which we have adopted in computing the data given in this paper. The transmission of the atmosphere above Mount Wilson is computed for the mean water-vapor content, 0.7 cm, from atmospheric transmissions given by the

[1] *Mt. Wilson Contr.*, No. 336; *Astrophysical Journal*, **66**, 43, 1927.

Smithsonian observers,[1] and from absorption-band measurements on a series of solar-energy curves which we made for the purpose. From the transmission-curves given in Figure 4, the spectral-energy curves of black bodies at various temperatures, and the reflection coefficients of silver, we have computed Table IV, which shows for black bodies of different temperatures the heat-index, water-cell absorption, and reduction to no atmosphere. The latter includes absorption by the atmosphere and the telescope.

TABLE IV

Absolute Centigrade Temperature	Computed			Reduction to No Atmosphere Δm_r
	Heat-Index		Water-Cell Absorption	
	λ 0.555 μ	λ 0.529 μ		
	Mag.	Mag.	Mag.	Mag.
24000°	+0.01	+0.01	+0.17	2.84
20000	0.01	0.01	0.18	2.35
16000	0.01	0.00	0.19	1.84
14000	0.00	0.00	0.20	1.57
12000	0.00	0.00	0.21	1.26
10000	0.02	0.05	0.24	1.00
8000	0.07	0.12	0.29	0.71
7000	0.12	0.18	0.32	0.60
6000	0.26	0.33	0.37	0.49
5000	0.48	0.59	0.46	0.41
4000	0.92	1.08	0.63	0.41
3000	1.91	2.24	1.00	0.48
2500	2.81	3.32	1.34	0.57
2000	4.33	5.16	1.93	0.71
1500	+7.29	+8.58	+3.03	0.96

The visual sensibility-curve of the eye depends on the intensity of the source. The form of the curve is little affected, but the maximum shifts from λ 0.51 μ for very faint sources to λ 0.56 μ for very bright sources. It might be thought that the effective wave-length which obtains in measurements of the Harvard magnitudes, which were made with the 4-inch meridian photometer, would correspond more nearly to λ 0.51 μ, but, when the visual sensibility-curve corresponding to this value is adopted, a system of temperatures results which disagrees with the water-cell values quite beyond the errors of measurement. The agreement is better when the curves for

[1] *Smithsonian Physical Tables* (7th ed.), p. 418, 1921.

brighter sources are used; but it seems hardly proper to use an effective wave-length much greater than λ 0.555 μ, and we have accordingly adopted this value as giving temperatures most consistent with those derived from the water-cell absorptions and as being not unreasonably far from the curves determined in the laboratory with

TABLE V

Spectral Type	Observed		Temperature			
	Heat-Index	Water-Cell Absorption	Heat-Index λ 0.555 μ	Heat-Index λ 0.529 μ	Water-Cell Absorption	Color-Index*
	Mag.	Mag.				
Bo	0.05	0.20	.....	.....	.....	23000°
B5	0.01	0.23	.....	.....	.....	15000
Ao	0.00	0.26	.....	.....	.....	11200
A5	0.02	0.30	.....	.....	7500°	8600
Fo	0.15	0.36	6750°	7300°	6200	7400
F5	0.30	0.41	5760	6160	5450	6500
gGo	0.47	0.50	5000	5450	4700	5500
gG5	0.65	0.60	4550	4870	4140	4700
gKo	0.90	0.70	4020	4300	3750	4100
gK5	1.57	0.93	3240	3480	3130	3300
gMo	1.86	1.01	3030	3250	2980	3050
gM2	2.2	1.14	2810	3000	2810	.....
gM4	3.1	1.30	2400	2590	2550	.....
gM6	4.2	1.46	2050	2200	2390	.....
gM8	5.2	1.62	1780	2000	2250	.....
Me Max	4.4	1.5	1990	2160	2350	.....
Me Min	8.9	2.2	.....	.....	1830	.....
dGo	0.32	0.42	5700	6100	5350	6000
dG5	0.39	0.47	5350	5750	4920	5600
dKo	0.55	0.54	4820	5100	4460	5100
dK5	1.10	0.76	3720	3980	3550	4400
dMo	1.40	0.87	3400	3650	3260	3400
dM2	2.1	1.14	2870	3060	2780	.....

* Russell, Dugan, and Stewart, *Astronomy*, **2**, 734, 1927.

sources whose order of brightness is that of stellar images seen with a 4-inch telescope. Brill,[1] in determining temperatures from color-index, adopted the value 0.529 μ, but this seems to be too small to fit the present data. The improvement in the agreement of temperatures determined from the water-cell absorptions with those determined from the heat-index, when the sensibility-curve with effective wave-length 0.555 μ, instead of 0.529 μ, is used, is illustrated in Table V. This table gives the observed heat-index and water-cell

[1] *Astronomische Nachrichten*, **231**, 330, 1927.

absorption taken from the mean curves in Figures 1 and 2, and the temperatures of giants and dwarfs of the various spectral classes read from Table IV. Column 13 of Table III gives, for a number of stars of special interest, the absolute temperatures which we have derived from the heat-index and water-cell measurements.

There seems no good reason why the heat-index should give such consistently higher temperatures than the water-cell absorption for stars earlier than G5, unless the assumption of black-body radiation or the adopted visual sensibility-curve is in error. Possibly both are contributing factors. The maximum radiation of stars earlier than G5 is near, or to the violet of, the effective wave-length of visual radiation; and, if these stars have an abnormal visual radiation much greater than that corresponding to the black-body curve, as has been observed in the case of the sun, the heat-index will lead to temperatures higher than those given by water-cell absorption. There can scarcely be any important instrumental error peculiar to our water-cell measurements, since, as shown in Figure 2, they agree well with the measurements of Coblentz.

TEMPERATURES FROM TOTAL RADIATION

In the case of stars for which the angular diameter has been measured by the interferometer, we may compute temperatures from the total radiation. This involves the reduction of radiometric magnitudes to no atmosphere and a determination of the radiation constant of a star of zero radiometric magnitude. The radiation equivalent of a star of zero radiometric magnitude was determined by calibrating the thermocouple with three different sources: the sun, a Hefner lamp, and a 100-watt nitrogen-filled incandescent lamp. The sun's energy was reduced by spreading the light reflected from a silvered plane mirror over a circle 1 meter in diameter by means of a 1-inch silvered spherical mirror of 2 inches focal length. The energy at several points along several radii of this circle was measured, and, from this distribution and the measured galvanometer deflections, the energy corresponding to a deflection of 1 mm was determined. This was corrected for absorption by the silvered surfaces, reduced to the zenith and to the mean distance of the sun. The value of 1.52 calories was used for the radiation constant of the

sun at the zenith on Mount Wilson. When compared with the observed deflections from 13 stars with well-determined radiometric magnitudes, this gave 16.3×10^{-12} cal cm^{-2} min^{-1} for a star of zero radiometric magnitude.

Measurements of a Hefner lamp at a distance of 3 meters were made both on Mount Wilson and in Pasadena. Those showed an increase of 7 per cent on Mount Wilson, probably because of less atmospheric absorption there. The radiation constant of the Hefner lamp has been determined by Coblentz at 2 meters. The reduction factor necessary to reduce our measurements to 2 meters was determined experimentally and was found to be 6 per cent greater than that computed from the inverse square law, in harmony with the measurements of Coblentz. Using Coblentz' value[1] of 156×10^{-5} cal cm^{-2} min^{-1} for the Hefner lamp at 1 meter, we obtain 17.1×10^{-12} cal cm^{-2} min^{-1} for the radiation from a star of zero radiometric magnitude.

The incandescent light was a condensed-filament nitrogen-filled lamp working at 98 watts. With such a lamp some power is consumed without radiation. A plot of galvanometer deflections against watts consumed over the range 0 to 100 watts shows a linear relationship when the power consumption exceeds 35 watts; below this limit the radiation falls off rapidly. A straight line drawn through the plot meets the power axis at 16 watts; hence the power radiated by this lamp was reduced from 98 watts to 82 watts. The distribution of radiation about the lamp was investigated, and in the direction in which the measurements were made the value was found to be 98 watts. This lamp gave 18.4×10^{-12} cal cm^{-2} min^{-1} for a star of zero radiometric magnitude.

In this connection it is interesting to note that the radiometric magnitude of the Hefner lamp at 1 meter, considered as a celestial object, is -20.00. Further, the brightness of the international candle is 1.11 Hefner units,[2] whence its radiometric magnitude is -20.11. Since the visual magnitude of the meter-candle is -14.18,[3] its heat-index is 5.82 mag. This corresponds to a temperature of 1900° K. The water-cell absorption of the Hefner flame, 2.7 mag.,

[1] *Bulletin of the Bureau of Standards*, 11, 87, 1914.

[2] *Smithsonian Physical Tables* (7th ed.), p. 260, 1921.

[3] *Ibid.*, p. 413.

which probably does not differ essentially from the standard candle, gives a temperature of 1700° K. Laboratory measurements[1] give about 1900° K for the temperature of a yellow gas flame.

The mean of the results obtained by the three methods gave the coefficient in the following equation:

$$E' = 17.3 \times 10^{-12} \times 2.5^{-m_r} \text{ cal cm}^{-2} \text{ min}^{-1}, \qquad (3a)$$

where E' is the energy in calories received per minute by the thermocouple from each exposed square centimeter of the concave mirror of the telescope, and m_r is the radiometric magnitude of the star. For no atmosphere and a telescope reflecting perfectly, this equation becomes

$$\log E = -10.7620 - 0.4\ (m_r - \Delta m_r), \qquad (3b)$$

where Δm_r is the reduction to no atmosphere, which includes the absorption by the atmosphere and the silver surfaces of the telescope. The values of the correction for various temperatures are given in Table IV. Equation (3*b*) was used to compute the total radiation in column 11 of Table III.

The absolute temperature, T, of a star is given by the relation

$$\log T = 2.638 - 0.1\ (m_r - \Delta m_r) - \tfrac{1}{2} \log d, \qquad (4)$$

where d is the diameter of the star in seconds of arc. As a first approximation we may enter Table IV with the heat-index or water-cell absorption and take Δm_r from column 4, repeating the calculation if necessary with a new value of Δm_r obtained from the provisionally calculated T.

The temperature T may be obtained from the water-cell absorption or from the heat-index and used to obtain the apparent diameter, d, in seconds of arc, from equation (4), written in the form

$$\log d = 5.276 - 2 \log T - 0.2\ (m_r - \Delta m_r). \qquad (5)$$

Table VI contains the measured diameters of stars observed by Pease with the interferometer, the temperatures computed from equation (4), and the diameters computed by equation (5) with

[1] Féry, *Journal de Physique*, **6**, 979, 1906.

temperatures derived from both heat-indices and water-cell absorptions. These stars are of late spectral class; and their diameters, computed from the radiometric data, which average 50 per cent greater than those determined with the interferometer, are affected by the deviation from black-body radiation shown in Figure 3. This deviation is in the right direction and approximately of the right amount to account for the difference between the calculated and the measured diameters. Column 14 of Table III gives the diameters computed from equation (5) for selected stars of special interest.

TABLE VI

Star	Diameter			Absolute Temperature Centigrade		
	Measured by Interferometer	Computed from W. C. Absorption	Computed from Heat-Index	Computed from Meas. Diameter and Rad. Mag.	Computed from W. C. Absorption	Computed from Heat-Index
Arcturus	0".020	0".031	0".028	4300°	3440°	3580°
Aldebaran	0.020	0.033	0.031	3890	3080	3170
Betelgeuse	0.047	0.071	0.076	3270	2700	2600
Antares	0.040	0.062	0.065	3270	2680	2620
β Pegasi	0.021	0.029	0.028	3140	2730	2730
α Herculis A	0.030	0.065	0.090	3320	2340	2030
o Ceti A (Max)*	0.056	0.038	0.073	2210	2610	1970

* Data for o Ceti interpolated from mean radiation curve for January 10–20, 1925, when Pease's measurements were made; values adopted, $m_r = -0.15$, W. C. = 1.26, $m_v = 4.3$, H.I. = 4.45.

BOLOMETRIC MAGNITUDES

The value of the bolometric magnitude of a star is given by the simple relation

$$m_b = m_r - \Delta m_r + (\text{H.I.} + \Delta m_r)_s ,$$

where $(\text{H.I.} + \Delta m_r)_s$ is the heat-index plus the reduction to no atmosphere for the particular star or class of stars for which the radiometric and bolometric scales of magnitude are made to coincide. Eddington[1] has chosen the brighter component of Capella as a basis for the theoretical computation of bolometric magnitudes, but the uncertainties in the relative brightness of the components of

[1] *Monthly Notices, R.A.S.*, **84**, 308, 1923.

Capella and in its parallax make this star unsatisfactory as a means of establishing the zero point of the magnitude scale. We have therefore taken the giants of class Go as the standard, and in determining the zero point have used the eight giants in Table III between F5 and G5, together with Procyon and ϵ Leonis. These stars give an average zero point for bolometric magnitude which differs from Eddington's by about 0.1 mag.

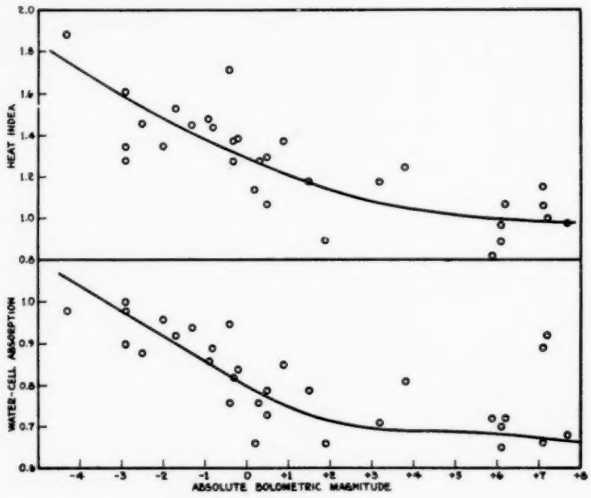

FIG. 5

The above equation then becomes

$$m_b = m_r - \Delta m_r + 0.9 ,$$

while the absolute bolometric magnitude is given by

$$M_B = m_r - \Delta m_r + 5 \log p + 5.9 = M_v - \text{H.I.} - \Delta m_r + 0.9 , \qquad (6)$$

where p is the parallax in seconds of arc, M_v is the absolute visual magnitude and H.I. the heat-index. The absolute bolometric magnitudes computed by formula (6) are given in column 12 of Table III.

The relation between absolute bolometric magnitude and heat-index is shown by the upper curve of Figure 5, and the similar relation for water-cell absorption by the lower curve. All the stars between spectral types G6 and M2 have been plotted in Figure 5 by

reducing their observed heat-indices and water-cell absorptions to type K4. Such a reduction is possible because the difference in water-cell absorption or heat-index between a star of type K4 and one of any other type within these limits is practically independent of its absolute bolometric magnitude. This is shown by Figures 1 and 2, in which the curves for giants and dwarfs of these types are approximately parallel. The variation of heat-index and water-cell absorption, and therefore of temperature, with absolute bolometric magni-

TABLE VII

Ten Brightest Stars in Order of Visual Magnitude				Ten Brightest Stars in Order of Radiometric Magnitude				Ten Brightest Stars in Order of Total Radiation Reaching the Solar System		
Star	Type	Vis. Mag.	Rad. Mag.	Star	Type	Rad. Mag.	Vis. Mag.	Star	Type	Cal cm^{-2} min^{-1} $\times 10^{-2}$
Sirius	A2s	−1.58	−1.27	Betelgeuse	M2	−1.67	+0.92	Sirius	A2s	145
* Canopus	F3	−0.86	−1.09	Antares	M1	−1.32	+1.22	Betelgeuse	M2	132
*α Centauri	G6	+0.33	−0.08	Sirius	A2s	−1.27	−1.58	Antares	M1	96
	K4	+1.70	+0.70	*Canopus	F3	−1.09	−0.86	*β Centauri	B1	83
Vega	A1s	+0.14	+0.10	*γ Crucis	M3	−1.0	+1.61	*Canopus	F3	77
Capella	Go	+0.21	−0.38	Arcturus	Ko	−0.98	+0.24	*γ Crucis	M3	69
Arcturus	Ko	+0.24	−0.98	Aldebaran	K5	−0.60	+1.06	Arcturus	Ko	64
Rigel	B8p	+0.34	+0.23	Capella	Go	−0.38	+0.21	*Achernar	B5	51
Procyon	F3	+0.48	+0.22	o Ceti max.	M6e	−0.2	+3.6	Rigel	B8p	50
* Achernar	B5	+0.60	+0.60	*α Centauri	G6	−0.08	+0.33	Spica	B3	48
*β Centauri	B1	+0.86	+0.81		K4	+0.70	+1.70			

* Computed from spectral type and visual magnitude; see Figure 1. The spectral type of γ Crucis was obtained from data furnished by the Lick and Harvard College Observatories.

tude for a given spectral type is even more marked among the giants than between the giants and dwarfs.

STARS OF PECULIAR INTEREST

Table VII lists the ten brightest stars in order of (1) their visual magnitude, (2) their radiometric magnitude, and (3) the total radiation reaching the solar system from the star.

In the list of ten brightest stars in order of total radiation reaching the solar system Spica appears to the exclusion of Aldebaran and o Ceti, principally on account of the large atmospheric absorption for a star of early type. While visually Sirius is by far the brightest star in the sky, radiometrically it stands third in the list, being excelled by Betelgeuse and Antares, both stars of class M.

Coblentz has called attention to a number of stars which he

suspected of having abnormal infra-red radiation because their water-cell transmissions were low (water-cell absorptions high). In each case he attributed the low water-cell transmission to a low-temperature companion. Table VIII is a comparison of the water-cell absorptions of these stars as observed by Coblentz with our measurements and with the values taken from the mean curve for giants belonging to the same spectral class. It will be seen that our measurements agree well with the mean curve, except in the case of Antares, for which there is a discrepancy of +0.13 mag. Cob-

TABLE VIII

Star	Type	Water-Cell Absorption				Heat-Index	
		Pettit and Nicholson		Coblentz		Pettit and Nicholson	
		Mean Curve	Observed	†Lick	‡Flagstaff	Mean Curve	Observed
Rigel	B8p	0.24	0.23	0.94	0.50	0.00	+0.11
Sirius	A2s	0.26	0.25	.....	{0.47 *0.24}	0.00	−0.31
Procyon	F3	0.40	0.43	.....	0.48	0.25	+0.26
Capella	G1	0.50	0.52	0.80	0.61	0.50	+0.59
Antares	M1	1.08	1.21	1.42	1.20	2.08	+2.54

* See correction in *Popular Astronomy*, **35**, 137, 1927.

† *Lick Observatory Bulletin*, **8**, 123 (No. 266), 1915.

‡ *Scientific Papers of the Bureau of Standards*, **17**, 743 (No. 438), 1922.

lentz' value for Antares is in good agreement with ours. The most serious disagreement is in the case of Rigel. It would seem that our value of the water-cell absorption, 0.23 mag., which is the mean of measurements made on fourteen nights distributed over the period October 28, 1921, to October 9, 1926, can hardly be seriously in error.

Sirius has an abnormal heat-index. Perhaps in this case, and, to a lesser extent, with the other stars in this list, which are all bright, the visual magnitude may be subject to some correction, which might reduce the discrepancy in the heat-index.

That spectroscopic and close visual binaries do not as a class have abnormal heat-indices or water-cell absorptions is shown by an inspection of Table III, in which they are indicated by asterisks in the first column. The average deviation of these

twenty-seven stars from the mean curves of heat-index and water-cell absorption against spectral class, read from Figures 1 and 2, or Table V, is +0.07 and +0.02 mag., respectively. The mean deviation of the twenty-three giants whose absolute magnitudes are brighter than −2 is only +0.10 mag. in heat-index and +0.04 mag. in water-cell absorption. This deviation seems to increase somewhat among the M stars, but there is no other spectral class particularly remarkable for the amount of these deviations.

ECLIPSING VARIABLES

Two bright stars of the eclipsing type, Algol and λ Tauri, have been studied, the former throughout principal minimum on two nights, November 6, 1923, and November 20, 1924. The results given in Table III are for maximum and minimum light. The range in radiometric magnitude of Algol, 1.22, is practically the same as that in violet radiation, namely, 1.20, found by Stebbins[1] with the photo-electric cell. The range observed in the visual region with the selenium cell[2] was 1.22 mag. Our radiometric measurements, which correspond to an effective wave-length of about 0.6 μ for a star of class B8, agree with this. The variations seem to be synchronous and of the same amplitude in visual and radiometric magnitude. Since the Harvard magnitudes of Algol are given to only one decimal, the values shown in Table III were obtained by applying to α Persei the difference in magnitude between it and Algol found by Stebbins.[3] There is no evidence of increased water-cell absorption as minimum is reached. A detailed account of our measurements on this star will be given in a future article.

No detailed observations were made on λ Tauri, but the water-cell seems to give no indication of a variation in type.

LONG-PERIOD VARIABLES

Ten of these stars have been measured in detail over a period of 5 years, the mean results for maximum and minimum radiation, which are synchronous with these phases in light, being indicated in Table III. The average heat-index, water-cell absorption, magni-

[1] *Astrophysical Journal*, **53**, 105, 1922.

[2] *Ibid.*

[3] *Ibid.*, **32**, 205, 1910.

tude, temperature, and diameter at various phases are given in Table IX.

It is probable that the temperatures from heat-index are too low on account of the strong absorption of titanium oxide in the atmospheres of these stars; the diameters have therefore been computed from water-cell absorptions, which are probably less affected in this way.

Table IX seems to show that the diameters of the long-period variables are greater at minimum than at maximum, the average at maximum being 0".025, and at minimum 0".029. The increase from

TABLE IX

	Mean Radiometric Magnitude	Heat-Index	Water-Cell Absorption	Temperature		d
				Heat-Index	Water-Cell Absorption	
Maximum	1.3	4.4	1.50	1990°	2350°	0".025
Minimum	2.2	8.9	2.17	1350	1830	0.029
Median	1.8	6.6	1.84	1550	2060	0.017
	Visual	Radiometric				
Range in magnitude	5.3	0.9				

minimum to maximum of 5.3 mag. visually and 0.9 mag. radiometrically is thus accompanied by a decrease of 12 per cent in diameter and an increase of 28 per cent in temperature. Most of the variation in radiation is thus accounted for by variation in temperature, and the residual which is explainable by change in diameter is relatively small, and might have either sign, depending on the adopted temperatures and corrections to no atmosphere. This, of course, is not the only possible interpretation of these radiometric measurements, since a change in the absorption of the star's atmosphere between maximum and minimum might produce a like result.

According to Merrill and Strömberg[1] the mean absolute visual magnitude of stars of classes M6e to M8e at maximum is +0.6. Applying equation (6) to the data in Table IX and using this value of the absolute visual magnitude, we find the absolute bolometric magnitude at maximum to be −3.5. Since the range is about 0.9

[1] *Mt. Wilson Contr.*, No. 267; *Astrophysical Journal*, **59**, 97, 1924.

mag., of which 0.15 is due to the change in atmospheric absorption between maximum and minimum, the absolute bolometric magnitude at minimum is -2.8, and the mean absolute bolometric magnitude -3.2. If we take the mean heat-index of the Cepheids from Table III to be 0.5 mag. and the correction to no atmosphere as 0.4 mag., the mean absolute bolometric magnitude of the long-period variables, -3.2, corresponds to that of a Cepheid variable of about 10 days' period. This result depends on Shapley's period-luminosity diagram[1] and an assumed mean spectral type[2] of G3 for the Cepheids.

CEPHEID VARIABLES

Two Cepheid variables, δ Cephei and η Aquilae, have been measured on about thirty nights. Their visual ranges are about 0.8 mag. and their radiation ranges 0.45 mag. The heat-indices and water-cell absorptions show changes with phase which indicate corresponding changes in spectral type. For δ Cephei the spectral type as read from the mean curve for giant stars is F2 at maximum and G2 at minimum. For η Aquilae the type is F9 at maximum and G9 at minimum. The results for δ Cephei are in close agreement with the spectral type observed by Shapley,[3] but for η Aquilae they are nearly a spectral division later than his values. Since these stars are intrinsically brighter than the giant stars from which the mean curve was drawn, one- or two-tenths of a spectral division should possibly be subtracted from the values read from the curve to correct for the difference of absolute magnitude. The calculated temperatures at minimum are in each case about 20 per cent lower than at maximum, and the diameters about 30 per cent less at maximum than at minimum. The heat-curves of these stars, which were obtained by combining observations extending over 4 years, are not as satisfactory as was to have been expected; and until these results are confirmed by further observations, they should not be given too much weight.

THE SUN AS A STAR

The water-cell absorption of the sun was determined on eight different days, both in Pasadena and on Mount Wilson, with three

[1] *Mt. Wilson Contr.*, No. 151; *Astrophysical Journal*, **48**, 279, 1918.

[2] *Harvard Circular*, No. 314, 1927.

[3] *Mt. Wilson Contr.*, No. 124; *Astrophysical Journal*, **44**, 273, 1916.

different thermocouples. Coelostats were used in several cases, and in others the thermocouple was fixed to an equatorial mounting with two silvered mirrors in the optical path. The water-cell absorption was measured from sunrise to late afternoon and was found to decrease from 0.50 mag. for air-mass 8 to 0.41 mag. near the zenith. This is 0.03 mag. less than the average water-cell absorption for a dwarf star of spectral class Go.

The heat-index, however, is somewhat abnormal. To obtain the radiometric magnitude of the sun, we may take the ratio in magnitudes of the solar constant, 1.93 cal cm^{-2} min^{-1}, to the radiation constant E' in equation (3*a*), where $m_r = 0$, and apply the atmospheric absorption for a star whose water-cell absorption is 0.41 mag.; or, for the solar constant we may substitute the observed solar energy, 1.52 cal cm^{-2} min^{-1}, at the zenith on Mount Wilson, and apply the absorption by reflection of two silver surfaces, 0.16 mag. for a star of type Go. The two methods agree within 0.03 mag. in assigning -27.18 as the radiometric magnitude of the sun. When Russell's reduction of the sun's visual magnitude, -26.72, is used, the resulting heat-index of the sun is 0.46 mag., which is 0.14 mag. higher than the average for a dwarf of type Go. Although this deviation from the mean curve is less than that of some of the other dwarfs, we have given the temperature in Table III from water-cell absorption alone, since there may be some uncertainty in the visual magnitude. From the radiometric magnitude and water-cell temperature of the sun we may compute its diameter from equation (5). This gives 2133″, a value 11 per cent higher than the micrometric diameter. This indicates the order of accuracy of stellar diameters computed from radiometric data.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
July 1928

THE SPECTROGRAPHIC TRIPLE SYSTEM 28 η ORIONIS A′A″−D

By ALEXANDER POGO

ABSTRACT

An *increase* of more than 20 km/sec. in the *velocity* of the *center of mass* of the spectroscopic binary A′A″, between the epochs 1925.8 and 1927.9, was derived from thirty-one spectrograms secured at the Mount Wilson (4 plates), Dearborn (10 plates), and Yerkes (17 plates) observatories.

The new γ-values, combined with those published since 1902, lead to the following *preliminary orbital elements* of the oscillation of *long period:* velocity of the triple system A′A″−D, +19.5 km/sec.; period, 9.2 years; epoch of periastron passage, 1900.0; longitude of periastron of A, 270°; eccentricity, 0.1; half-amplitude of oscillations of A, 17.5 km/sec.; major semi-axis of the inclined absolute orbit of A, 800 million km; function of mass of satellite D, 1.84 ⊙.

Assuming a small relative inclination of the long-period orbit and of the orbit of the eclipsing binary A′A″, the mass of the third body D is found to be 13.1 ⊙, of the same order as the masses 11.2 of A′ and 10.6 of A″; the total, about 35 ⊙, is normal for a system of early B-type stars. The *mean distance* between the spectroscopic binary A′A″ and the third star D is about 14.3 astronomical units. With the Mount Wilson spectroscopic parallax of 0″.007, the *maximum angular separation* of the stars A and D would be of the order of 0″.1.

The observations made at *Vienna* in 1920.2, characterized by the unexplained *shift in phase* of about 3 days, could be reduced not only with the established period of almost exactly 8 days, but also with 8/7 and 8/9 of a day, in accordance with the rule of *alternative periods*. The periods of about one day *do not*, however, *satisfy* the numerous *American* observations.

The brightest member, A, of the visual multiple[1] system 28 η Orionis (1900: $\alpha = 5^h19^m.4$; $\delta = -2°29'$) was the first star found with the Bruce spectrograph to be a spectroscopic binary. This discovery was made, in 1901, by E. B. Frost[2] and W. S. Adams. A year later Adams[3] computed the first orbital elements of the binary; he found a period of 7.9896 days.

In 1915, A. F. Beal[4] found, from his measurements of the Allegheny spectrograms secured in 1909.4 and 1915.0, that the velocity

[1] The remote (115″) and faint (10^m) companion C discovered by W. Herschel in 1781, and the close (1″) and bright (4^m.9) companion B discovered by W. R. Dawes in 1848, seem to form, with the 3^m.7 star A, a dynamical system. According to the *Henry Draper Catalogue*, the combined photometric magnitude of the visual system is 3.44; the spectral class of the star A is B1.

[2] *Publications of the American Astronomical Society*, **1**, 179, 1902.

[3] *Astrophysical Journal*, **17**, 68, 1903.

[4] *Publications of the American Astronomical Society*, **3**, 117, 1915.

of the center of mass varies, the period of this oscillation being between 9 and 10 years.

TABLE I

SPECTROGRAPHIC MATERIAL, 28 η ORIONIS A′

No.	Plate	Midexposure G.M.T.	Obs.	Wt.	Phase	Vel.	O.−C.
					days	km/sec.	km/sec.
1	IR 7855	1925 Aug. 22.935	σ, S	1.0	1.772	− 20	+ 4
2	IR 7876	Sept. 2.898	σ, S	.7	4.746	+ 88	−34
3	IR 7900	Sept. 23.940	B, S	1.0	1.820	− 15	+ 3
4	γ 13769	Sept. 27.999	Sf	1.0	5.879	+ 16	+ 1
5	IR 7918	Oct. 14.871	B, S	.7	6.773	− 93	−11
6	C 3587	Dec. 2.838	Sf	1.0	7.804	−137	+ 4
7	C 3591	Dec. 3.858	Sf	1.0	0.835	−118	− 5
8	γ 14052	1926 Feb. 24.765	Sf	1.0	3.850	+133	−13
9	DO 437	Nov. 20.873	E	.7	1.324	− 73	− 2
10	DO 745	1927 Apr. 5.562	E	1.0	1.196	− 36	+25
11	DO 746	Apr. 5.602	E	1.0	1.236	− 59	− 1
12	DO 753	Apr. 10.590	E	1.0	6.224	+ 28	+30
13	DO 760	Apr. 16.576	E	.3	4.221	+171	+ 5
14	DO 766	Apr. 17.569	E	1.0	5.214	+ 74	−33
15	DO 772	Apr. 19.580	E	.7	7.225	− 80	+15
16	DO 997	Sept. 18.919	E	.7	7.769	−106	+13
17	DO 1007	Sept. 20.929	E	.7	1.789	+ 3	+ 3
18	DO 1035	Oct. 9.919	E	.7	4.801	+ 97	−44
19	IR 8618	Nov. 12.808	B. H, S	.7	6.733	− 45	+11
20	IR 8632	Dec. 15.662	B, H, S	.7	7.630	− 99	+16
21	IR 8769	1928 Mar. 2.585	P, S	1.0	5.661	+ 79	+18
22	IR 8777	Mar. 3.580	P, S	.7	6.656	− 47	+ 1
23	IR 8781	Mar. 4.565	σ, P	.7	7.641	−110	+ 5
24	R 1295	Mar. 7.551	σ, P, S	1.0	2.638	+ 95	+ 1
25	IR 8790	Mar. 17.523	σ, P	.7	4.621	+147	− 4
26	IR 8800	Mar. 18.540	σ, P, H	1.0	5.638	+ 68	+ 4
27	IR 8809	Mar. 21.530	σ, P	.7	0.638	−107	− 4
28	IR 8818	Mar. 22.533	σ, P	.7	1.641	− 5	+11
29	IR 8831	Mar. 27.530	σ, P, H	.7	6.638	− 6	+40
30	IR 8838	Mar. 30.533	σ, P	.7	1.652	− 31	−16
31	IR 8857	Apr. 1.533	σ, P	.7	3.652	+166	+ 2

The names of the observers are abbreviated as follows: B=S. B. Barrett, E=C. T. Elvey, H=C. Hujer, P=A. Pogo, Sf=R. F. Sanford, σ=O. Struve, S=F. R. Sullivan.

R. F. Sanford[1] discussed, in connection with his own observations of the system, the results obtained by Adams, Beal, F. Schlesinger and R. H. Baker,[2] and by A. Hnatek;[3] he found that the elements of Adams represent all the American observations, pro-

[1] *Astrophysical Journal*, **64**, 172, 1926.

[2] *Publications of the Allegheny Observatory*, **1**, 136, 1910.

[3] *Astronomische Nachrichten*, **217**, 53, 1922.

vided that an improved period, $P = 7^d.98922$, be employed. Adopting a period of 9.5 years, he gave a provisional curve of the γ-values.

Table I contains the spectrographic material secured since the autumn of 1925 at the Mount Wilson, Dearborn, and Yerkes observatories. The data concerning Plates 4, 6, 7, and 8 are based on Table II of Sanford's paper. C. T. Elvey kindly put at our disposal his measurements of Plates 9 to 15. The remaining Dearborn plates[1] were measured by the writer. For the reduction of his measurements

TABLE II

VALUES OF γ OF THE SPECTROSCOPIC BINARY 28 η ORIONIS A'A''

EPOCH	INTERVAL		PLATES	WT.	PHASE	γ	O.–C.
	Days	Periods					
					years	km/sec.	km/sec.
1902.1	127	15.9	21	1.00	2.1	+35.5	−1.5
1902.8	77	9.6	7	.75	2.8	35.5	+0.8
1909.4	296	37.0	27	.75	0.2	24.8	+2.4
1915.0	105	13.1	17	.75	5.8	9.4	+1.0
1920.2	46	5.8	13	.50	1.8	37.0	+0.2
1923.8	.....	.....	1	.25	5.4	7.0	−4.9
1924.9	86	10.7	12	.75	6.5	7.0	+3.2
1925.8	186	23.3	8	.50	7.4	2.0	−0.2
1926.9	.....	.....	1	.25	8.5	2.0	−7.9
1927.9	362	45.3	22	.50	0.3	+24.0	+0.1

Weights were assigned according to the quality and number of observations, their distribution in phase, the scattering in radial velocities of A', and the shortness of the interval covered.

of the Yerkes one-prism spectrograms, the writer used the table recently computed by O. Struve and L. D. Cable.

The measures of the spectral lines of A'' are not included in Table I; when plotted, they indicate a curve of a somewhat larger amplitude than the velocity-curve of A'; the mass-ratio $m''/m' = 0.95$ is well established by the Allegheny observations of 1909.4.

The time of exposure (about 20 min. for one-prism spectrograms on Eastman 40 plates) being usually insufficient for recording measurable H and K lines of Ca^+, no attempt was made to include them in this study. They have a constant velocity, according to V. M. Slipher.[2]

[1] Kindly loaned by Director P. Fox.

[2] *Lick Observatory Bulletins*, 11, 171, 1925.

The velocities given in Table I are derived mainly from measurements of Hβ, Hγ, and the He-lines at λ 4388 and λ 4471. On the three-prism spectrogram, R 1295 (comparison spectrum of Ti-spark), very sharp lines due to Si^{++} and O^{+} were measured, in addition to the He-line at λ 4471; the velocity derived from this plate is

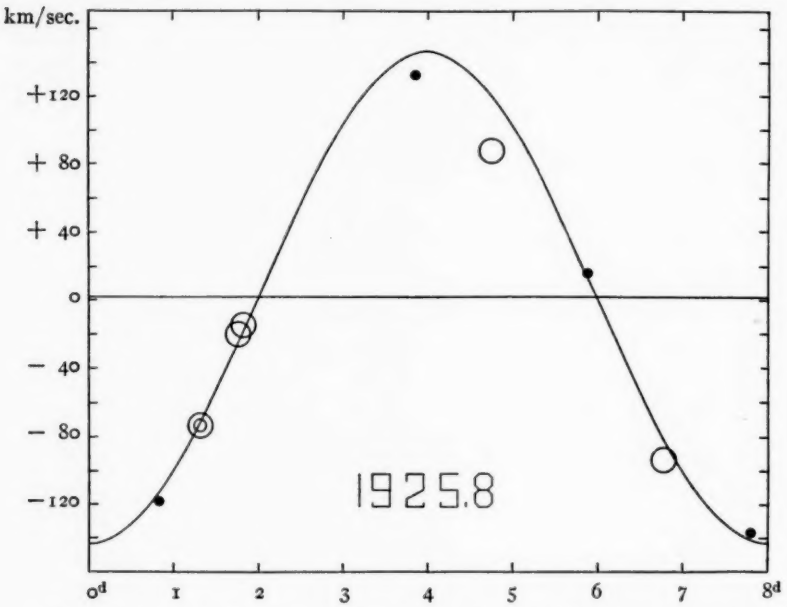

FIG. 1.—Radial-velocity curve of 28 η Orionis A′. Phase zero corresponds to J.D. 2415723.849 G.M.T. Yerkes observations are represented by circles, Mount Wilson observations by dots. The double circle represents the Dearborn observation of 1926.9.

probably of the same order of reliability as the early velocities of Adams.

The curves of Figures 1 and 2 correspond to circular motion; their half-amplitude represents $K = 145$ km/sec; phases are counted from J.D. 2415723.849 G.M.T., the epoch of a maximum negative value of the curve of Adams.

Sanford has found a velocity of +7.2 km/sec. for the center of mass of the spectroscopic binary A′A″, for the epoch 1925.0.

By adding the Yerkes observations secured in the fall of 1925, we can form two groups of velocities, the corresponding epochs being

1924.9 and 1925.8. The first group gives the value $\gamma = +7$ km/sec., while for the second group this value leads to negative residuals exclusively. We have therefore adopted, for 1925.8, the value $\gamma = +2$ km/sec. Figure 1 shows that the isolated Dearborn observation of 1926.9 suggests a value of γ of the same order. Similarly, the iso-

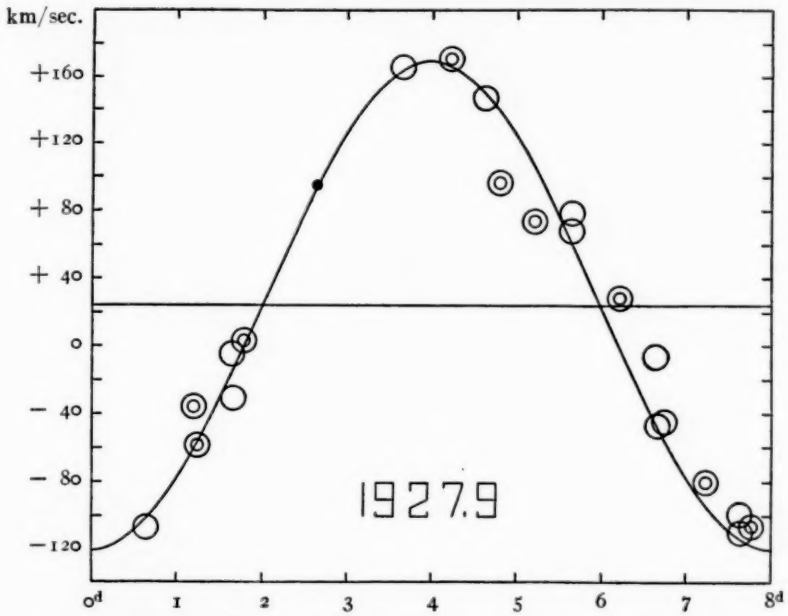

FIG. 2.—Radial-velocity curve of 28 η Orionis A′. Phase zero corresponds to J.D. 2415723.849 G.M.T. Yerkes observations are represented by circles, Dearborn observations by double circles. The dot represents observation No. 24.

lated Mount Wilson observation of 1923.8 fits well the curve of 1924.9, not reproduced here.

The Dearborn and Yerkes observations of 1927.9 show clearly that the radial velocity γ of the center of mass of the spectroscopic binary A′A″ considerably increased since 1925.8. In spite of the scattering of the velocities derived from one-prism plates, the value $\gamma = +24$ km/sec. can be considered as a satisfactory estimate (see Fig. 2). During the interval covered by the plates secured in 1927 and 1928, the value of γ continually changed; in the beginning of 1928, the velocity of the center of mass of A′A″ certainly had

reached the 25 km/sec. level, as the three-prism spectrogram of March 7 clearly shows.

By forming two groups of the very reliable results of Adams, covering two seasons of observation with the three-prism spectrograph, we see that the value of γ did not differ much from 36 km/sec. between the epochs 1902.1 and 1902.8.

The values of γ collected in Table II are plotted in Figure 3. The adopted value of the long period is 9.2 years. A period of about

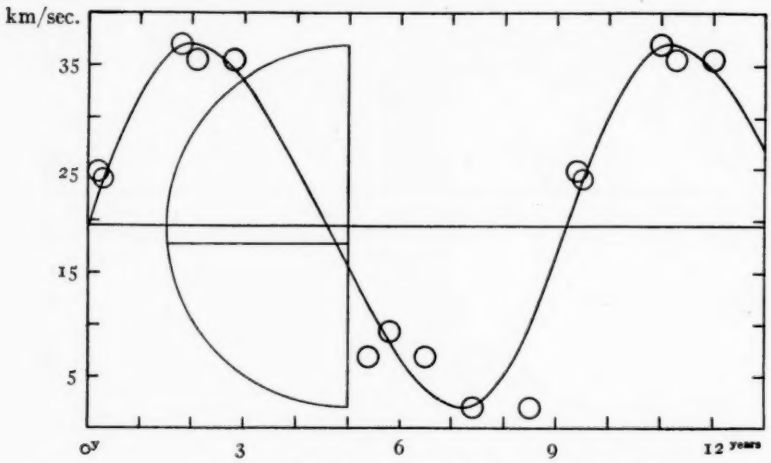

FIG. 3—Long-period radial-velocity curve of 28 η Orionis A'A". Phase zero corresponds to 1900.0.

6 years would satisfy all the American observations; but for the observations made at Vienna in 1920.2, the discrepancy would be of the order of the amplitude of oscillation.

The application of the hodographic method[1] to the free-hand velocity-curve indicated a longitude of periastron of about 270° and an eccentricity of the order of one-tenth. Figure 3 represents the velocity-curve computed with the orbital elements collected in Table III. The residuals are given in the last column of Table II. In spite of the apparently satisfactory agreement, these elements are given only provisionally, since future observations are liable to

[1] A. Pogo, *Astrophysical Journal*, **67**, 262, 1928.

necessitate further adjustments of the long period, and, therefore, of the other orbital elements.

J. Kunz and J. Stebbins[1] observed the short-period system A′A″ as an eclipsing binary, with a range of at least 0.15 magnitude at the principal minimum, and of 0.02 or 0.03 magnitude at the secondary minimum. The inclination of the short-period orbit to the line of sight is therefore so small that the value of sin i cannot differ

TABLE III

ORBITAL ELEMENTS OF THE SYSTEM OF LONG PERIOD, 28 η ORIONIS A′A″−D

Element	Designation	Value
Velocity of system	γ_{AD}	+19.5 km/sec.
Period	P	9.2 years
Time of periastron passage	T	1900.0
Longitude of periastron	ω_A	270°
Eccentricity	e	0.1
Half-amplitude	K_A	17.5 km/sec.
Function of mean distance	$a_A \sin i$	805,000,000 km
Function of mass	$\frac{(m_D \sin i)^3}{(m_A+m_D)^2}$	1.84 ⊙

much from unity, and the dimensions and masses of the spectroscopic system A′A″ from the following values:

$$a' = 15{,}900{,}000 \text{ km}$$

$$a'' = 16{,}800{,}000 \text{ km}$$

$$m' = 11.2 \odot$$

$$m'' = 10.6 \odot.$$

If we assume, with Sanford, that the relative inclination of the planes of the orbits of short and of long period is also small, the mean distance of the spectroscopic binary A′A″ from the center of mass of the long-period system A′A″−D is of the order of

$$a_A = 805 \cdot 10^6 \text{ km or } 5.4 \text{ astron. units,}$$

and the mass of the third body D,

$$m_D = 13.1 \odot .$$

[1] *Publications of the American Astronomical Society*, 3, 272, 1916.

The mean distance of D from the center of mass of the system A′A″−D would therefore be of the order of

$$a_D = 1{,}340 \cdot 10^6 \text{ km or } 8.9 \text{ astron. units,}$$

and the mean distance between the spectroscopic binary A′A″ and the third star D,

$$a_{AD} = 2{,}145 \cdot 10^6 \text{ km or } 14.3 \text{ astron. units.}$$

TABLE IV

PARALLAX OF 28 η ORIONIS

Method	Value	Authority
Statistical*	+0″.0058	H. C. Plummer†
Statistical‡	.0053	C. V. L. Charlier§
Spectroscopic	.007	W. S. Adams and A. H. Joy‖
Group-motion	.007	
Spectroscopic	.006	D. L. Edwards¶
Group-motion	.006	
Revised spectroscopic	.010	D. L. Edwards**
Trigonometric, relative	+0″.002 ±0″.007	S. A. Mitchell††

* Based on galactic motions of B-type stars.

† *Monthly Notices, R.A.S.*, **73**, 177, 1913.

‡ Based on spectral type and absolute magnitude.

§ *Meddelanden från Lunds Astronomiska Observatorium*, Ser. 2, No. 14, p. 67, 1916.

‖ *Astrophysical Journal*, **57**, 300, 1923.

¶ *Monthly Notices, R.A.S.*, **84**, 371, 1924.

** *Monthly Notices, R.A.S.*, **87**, 377, 1927.

†† *Memoirs of the National Academy of Sciences*, **22**, No. 1, 68, 1927, or *Publications of the Leander McCormick Observatory*, **4**, 68, 1927. In the preliminary announcement, in the *Astronomical Journal*, **36**, 143, 1926, the relative parallax was given, erroneously, as 0″.020±0″.007, and the absolute parallax as 0″.023.

The total mass of the system A′A″−D, about 35$\odot$, is normal for an early B-type star.

Table IV gives the different determinations of the parallax of the system (spectrum of A, photographic images of AB).

With a parallax of 0″.007, the maximum angular separation of the stars A and D would be of the order of 0″.1. Even if we accept the trigonometric absolute parallax, 0″.005, the maximum angular separation of the stars A and D remains within the reach of an interferometer, provided that the light of the visual companion B could be eliminated.

Since we assume that the long-period orbit is seen almost edge-on, the adopted value of the longitude of periastron, $\omega_A = 270°$, would make the line of apsides almost coincide with the line of sight. According to Figure 3, the satellite D was in superior conjunction with the spectroscopic binary A′A″ at the epoch of periastron passage, 1927.6, and will be in inferior conjunction in 1932.2. Interferometric observations of 28 η Orionis A, made around the epoch of maximum elongation of D, in the spring and autumn of 1929, may conceivably reveal the companion D at a distance of about 0″.1.

Sanford called attention to the curious fact that the observations made by Hnatek in February and March, 1920, at Vienna, can be well represented by the curve satisfying all the American observations, provided that the curve be shifted to the right by an amount corresponding to about 3 days.

The latitude of Vienna being 48°, the observations of a southern star are necessarily limited to small hour angles. The sidereal time of mid-exposure did not change considerably during the seven weeks of the Vienna observations. Under such circumstances, two periods of about 1 day should also represent the observations, in addition to the established period of about 8 days, according to the relations

$$p_1 = P/(P-1)$$

$$p_2 = P/(P+1)\,,$$

extended by O. Struve[1] from variable star work to spectroscopic binaries.

Three sets of phases were computed for the Vienna observations, with the Sanford period, and with the two corresponding short periods; in all three cases, J.D. 2422354.902 G.M.T., computed epoch of the 830th minimum velocity since J.D. 2415723.849, was taken as phase zero. The period of 8 days produced the unexplained shift of 3 days to the right, the observed velocities otherwise fitting closely a sine-curve. The period of 8/7 of a day indicated a steep

[1] *Astrophysical Journal*, **66**, 113, 1927. See also *Popular Astronomy*, **36**, 411, 1928. H. Ludendorff mentions, in the *Sitzungsberichte der Preussischen Akademie der Wissenschaften, physikalisch-mathematische Klasse*, 1924, sec. ix, p. 59, the possibility of 1-day periods—as an empirical rule, without indication of the relation between the long and the short periods.

descending branch of the velocity-curve. The period of 8/9 of a day indicated, in spite of some scattering of the velocities, a periastron point on the ascending branch.

It was found, however, that periods of about 1 day do not satisfy the spectrographic observations made in America under more favorable conditions, with considerable hour angles both East and West. The Sanford value, $P = 7^{d}.98922$, corresponds therefore to the only acceptable period.

A repetition of spectrographic observations of this bright star by a European observatory would undoubtedly solve the problem presented by the systematic shift in phase of the Vienna observations of 1920.2.

The photometric study of the eclipsing binary 28 η Orionis A′A″, inconvenient for one observer because of the very small difference between the length of 1 period and 8 days, could also be considerably simplified by the co-operation of several observers located at different longitudes.

YERKES OBSERVATORY
August 1, 1928

A SPECTROSCOPIC STUDY OF THE VISUAL BINARY SYSTEMS ζ HERCULIS AND β DELPHINI

By Y. C. CHANG

ABSTRACT

ζ Herculis has a period of 34.5 years. Its spectroscopic orbit could be determined from the available observations of the radial velocity. *The sign of the inclination* is found to be negative. *Its spectroscopic elements* are

$$K=4.6 \text{ km/sec.}, \quad \gamma=-69.8 \text{ km/sec.}, \quad a \sin i=707{,}600{,}000 \text{ km}, \quad \frac{m_2^3 \sin^3 i}{(m_1+m_2)^2}=0.089 .$$

A formula relating the mass-ratio and the parallax explicitly has been obtained in the form

$$\frac{M}{p}=\frac{a_1}{Aa}, \text{ where } M=\frac{m_2}{m_1+m_2} .$$

The average of trigonometric and other parallaxes gives $p=0''.099$, from which $m_2/m_1=0.88$.

6 *β Delphini*, discovered by Burnham as a close visual binary in 1873, has been observed for radial velocity for a time interval longer than its period of revolution of 26.8 years. The following facts are obtained from a study of its velocity-curve determined from Yerkes spectrograms:

$$K=6.8 \text{ km/sec.}, \quad \gamma=-21.0 \text{ km/sec.}, \quad a \sin i=857{,}000{,}000 \text{ km},$$
$$\frac{m_2^3 \sin^3 i}{(m_1+m_2)^2}=0.263, \quad m_2/m_1=1 .$$

The inclination is positive.

ζ HERCULIS

ζ Herculis is a visual binary (β 7717 = Σ 2084) with components of magnitudes 3.0 and 6.5. Its position for 1900 is $\alpha=16^h37^m.5$, $\delta=+31°47'$. The *Henry Draper Catalogue* gives its spectral type as Go. A definitive orbit has been derived by Comstock from visual observations extending over a period of more than two revolutions.[1]

The radial velocity of this star has been determined at the Lick Observatory since 1897, and the star was announced as a spectroscopic binary by Wright.[2] The values derived from thirty three-prism spectrograms are given in the *Publications of the Lick Observatory*, **16,** 245, 1928. With the velocity-curve computed from the

[1] *Astronomical Journal*, **30,** 145, 1916.

[2] *Lick Observatory Bulletin*, **1,** 159, 1902.

visual elements, it was found that maximum radial velocity should occur in the neighborhood of the year 1928. At my request, Dr. Otto Struve has made two observations with the Bruce spectrograph of the Yerkes Observatory with a dispersion of three prisms in April, 1928. Both spectrograms give very good and sharp lines. The spectrogram R 1317, taken on April 27.79, gives a velocity of −65.3 km/sec.; while the spectrogram R 1327, taken on April 28.91 yields a value of −66.3 km/sec.

Upon the selection of a proper scale, the relative velocity-curve computed with elliptic rectangular co-ordinates[1] fits the observations of Lick and of Yerkes exceedingly well, and the time of periastron passage is well represented. In view of the fact that the extreme variation of the radial velocity is only about 9 km/sec., the observed scattering of one or two km/sec. must be considered as well within the uncertainty of observation and measurement. Therefore the computed curve will be regarded as final. In other words, we assume that the elements e, ω, and T of the spectroscopic orbit are the same as those of the visual orbit.

The O.−C. for the Lick observations, when chronologically arranged, are +0.4, +1.3, +1.0, +1.7, +0.8, −1.0, +0.4, −0.1 −0.7, 0.0, 0.0, +0.7, +0.8, −0.2, +0.1, +0.5, −1.2, −0.9, +2.6, +1.1, +0.6, +0.4, −1.4, −0.4, −0.6, −2.1, −1.8, +0.4, +0.7, −0.8, −0.4. Those for the spectrograms of Yerkes are +0.8 and −0.2. Figure 1 represents the computed curve as related to the observed radial velocities. The value of K is determined from this curve.

Elements of Visual Orbit	Spectroscopic Elements*
$P=$ 34.46 years	$K=$ 4.6 km/sec.
$T=1898.77$	$\gamma=-69.8$ km/sec.
$e=$ 0.458	$a \sin i=707{,}600{,}000$ km
$a=$ 1".35	$a=959{,}700{,}000$ km
$\Omega=$ 51°.6	$\frac{m_2^3 \sin^3 i}{(m_1+m_2)^2}=0.089$
$i=$ 132°.5	
$\omega=$ 66°.7	$\frac{m_2^3}{(m_1+m_2)^2}=0.223$
$n=-10°.447$	

* In *Veroeffentlichungen der Univ. zu Berlin-Babelsberg*, V, 72, Arthur Beer gives a set of spectroscopic elements based upon radial velocities observed up to 1902.

[1] *Bulletin of the Astronomical Institute of the Netherlands*, 3, 149, 1926.

If we adopt the usual convention[1] as to the sign of i, the inclination of the orbit is found to be negative as the velocity-curve shows that the companion is approaching when at Ω (with respect to the center of mass).

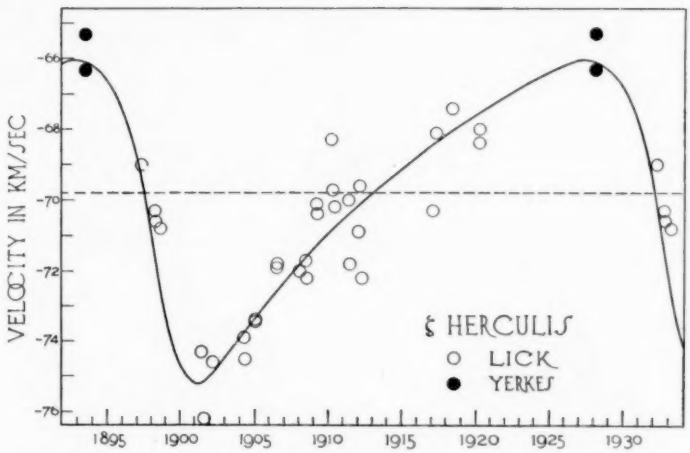

FIG. 1

When we have both the spectroscopic and the visual orbit of a binary system, we can determine the parallax on assuming the mass-ratio of the components, or we can determine the mass-ratio if a good value of the parallax be known. All determinations of the parallax of ζ Herculis known to me are the following:

TABLE I

Observer	Observatory	Parallax		Method
M. F. Smith	Yale	+0.172	±0.040	Heliometer
H. N. Russel	Cambridge	+0.101	±0.024	Photographic
A. S. Flint	Washburn	+0.146	±0.029	Meridian Cir.
J. O. Miller	Sproul	+0.086	±0.004	Photographic
Adams and Joy	Mt. Wilson	+0.066	±0.006	Spectroscopic
Van Biesbroeck and Pettit	Yerkes	+0.095	±0.010	Photographic
Schlesinger and Deaton	Allegheny	+0.114	±0.012	Photographic
Adams	Mt. Wilson	+0.076		Spectroscopic
Alden	Leander McCormick	+0.116	±0.008	Photographic

[1] Aitken, *The Binary Stars*, p. 73.

It is convenient to have a formula which involves explicitly the mass-ratio and the parallax. Then, as soon as both the spectroscopic and the visual orbits are determined, we shall have a formula which will yield immediately one of these two quantities when the other is known or assumed.

From the well-known relations[1] in the problem of two bodies,

$$k^2(m_1+m_2)=\frac{(2\pi)^2a^3/p^3}{P^2} \tag{1}$$

$$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i=\frac{(2\pi)^2}{k^2A^3}\frac{(a\sin i)^3}{P^2}, \tag{2}$$

we derive at once the equation involving the mass-ratio and the parallax explicitly

$$\frac{M}{p}=\frac{a_1}{Aa}, \tag{3}$$

where m_1 and m_2 = masses of the primary and the companion, respectively; a_1 = semi-major axis of the orbit described by the primary around the center of gravity of the system in kilometers; a = semi-major axis of the orbit of the companion relative to the primary, expressed in seconds of arc; A = astronomical unit in kilometers = 149,500,000 km, log $1/A$ = [1.82536 − 10], p = parallax, $M=\frac{m_2}{m_1+m_2}$ = mass-ratio.

Employing the value of a_1 and a as given above, we obtain for ζ Herculis

$$M/p=4.758.$$

Omitting the two values of the parallax determined by heliometer and meridian circle, and adding +0″.005 to the photographic values, the average of all the values in the above list is 0″.099. Introducing this value as the parallax of ζ Herculis, the mass-ratio comes out to be 0.471, or $m_1/m_2=0.88$. For stars of the types $F5-G0$, the average masses of the primary and the companion as given by Redman[2] is 1.2 and 1.0, respectively. The mass-ratio of ζ Herculis comes out exceedingly close to this average, although the magnitude of its secondary component is fainter than the average by about one magnitude.

[1] Aitken, *The Binary Stars*, p. 202. [2] *Monthly Notices, R.A.S.*, **88**, 33, 1927.

6 β DELPHINI

The position of 6 β Delphini is $\alpha = 20^h 32^m.9$ $\delta = +14°15'$ for 1900. The *Henry Draper Catalogue* gives its spectral type as F5, its magnitude as ptm = 3.72 ptg = 4.14. The close binary system A and B was first discovered by Burnham in 1873. The magnitudes of the primary and the companion are 4.0 and 5.0, respectively.

Spectroscopic observations of this system began at the Yerkes Observatory in 1905. There are twenty-five spectrograms up to the present, chiefly with dispersion of one prism. Due to the difference in magnitude of the components, the spectrum of only the principal star shows on the plate. Table II gives the date (G.M.T. before 1925, and U.T. after that) and the radial velocity of these spectrograms. For plates of one-prism dispersion, the radial velocity as reduced by the writer is from the measurement of a set of seven selected star lines. A number of plates were remeasured with the Hartmann spectrocomparator. An appreciable variation in the radial velocity has been found to exist among spectrograms taken at rather short intervals. It is not impossible that the principal star is itself a spectroscopic binary.[1] Since we are here merely dealing with the long-period system, I have taken the average radial velocity for each year and have tabulated the annual normal in the seventh column of Table II. Similarly Table III gives the average radial velocity for each year of the determinations from three-prism plates taken at the Lick Observatory.[2] The agreement of the values determined at the two observatories would be improved somewhat if systematic corrections were applied for the Yerkes velocities.[3]

The values of the mean radial velocity are plotted in Figure 2. With proper adjustment of scale, a velocity-curve computed from the visual elements is passed through these points. The amount of scattering of the points from the theoretical curve is given in the last columns of Tables II and III. On account of the fair agreement between the observations and the computed curve, and the accuracy of the visual orbit, the visual elements are again adopted for the spectroscopic orbit.

[1] The radial velocity of this is found to be variable by H. C. Wilson, *Lick Observatory Bulletin*, **6**, 148, 1911.

[2] *Publications of Lick Observatory*, **16**, 302, 1928. [3] *Ibid.*, **16**, xxxi, 1928.

TABLE II

YERKES RADIAL VELOCITY OF 6 β DELPHINI

Plate	G.M.T.	Obser. By	Meas. By	Quality	Vel.	Mean of Meas.	Mean for the Year	O.−C.
					km/sec.			km/sec.
IB 560..	1905 July 17.951	B S	σ Ch	g	−21.0 −18.5	−19.8	−19.8	+0.6
IIB 81..	1906 Aug. 31.598	B S	ECA Ch	f	−25.5 −30.5	−28.0	−28.0	−4.7
IB 2727..	1911 June 11.943	B S	ECA Ch	g	−26.5 −28.4	−27.4		
IB 2754..	July 3.766	L S	ECA Ch	p	−23.4 −25.1	−24.2	−24.7	−3.6
IB 2768..	July 17.766	L S	ECA Ch	g	−22.5 −22.4	−22.5		
IB 6503..	1922 May 12.899	σ S	σ Ch	g	−22.5 −19.5	−21.0		
IB 6504..	May 12.912	σ S	σ Ch	g	−17.1 −15.9	−16.5	−15.7	+0.8
IB 6509..	May 15.864	σ S	Ch	g	−13.4	−13.4		
IB 6515..	May 22.849	σ S	σ Ch	g	−15.7 − 8.0	−11.8		
IB 6982..	1923 July 9.769	σ S	Ch Ch Ch	f	−25.1 −17.1 −10.0	−17.4		
IB 6993..	July 13.815	σ S	Ch Ch	f	−12.2 −14.4	−13.3		
IB 7007..	July 16.894	σ S	Ch Ch	g	−24.3 −20.7	−22.5		
IB 7014..	July 25.812	σ S	Ch Ch	f	−18.2 −14.1	−16.2	−15.1	+1.3
IB 7049..	Aug. 18.844	σ S	Ch Ch	g	− 7.2 − 5.0	− 6.1		
IB 7083..	Sept. 3.649	σ S	Ch Ch	g	−14.7 −11.4	−13.0		
IB 7089..	Sept. 8.587	σ S	Ch Ch	g	−17.7 −14.0	−15.8		
IB 7431..	1924 June 30.890	σ S	Ch	f	−10.4	.....		
IB 7481..	Sept. 5.688	σ S	Ch	p	−15.0	.....	−16.6	−0.3
IB 7487..	Sept. 12.723	σ S	Ch	f	−24.5	.....		
IB 7766..	1925 June 6.388	σ S	Ch	p	−16.6	.....		
IB 7778..	June 29.371	σ S	Ch	p	−14.3	.....	−16.1	+0.2
IB 7785..	July 5.384	σ S	Ch	g	−17.3	.....		
R 1341..	1928 May 13.395	B S	σ Ch	g	−16.9 −12.8	−14.8		
R 1343..	May 14.399	B S	Ch	p	−17.3	−17.3	−17.0	+0.2
R 1346..	May 22.344	Mgn S	σ Ch	g	−21.2 −16.9	−19.0		

B = S. B. Barrett. S = F. R. Sullivan. σ = Otto Struve. Ch = Y. C. Chang. ECA = E. C. Arbogast. Mgn = W. W. Morgan. L = O. J. Lee.

From the curve, we find that at the ascending node the primary is approaching with respect to the center of mass. The sign of the

TABLE III

ANNUAL NORMALS OF THE LICK RADIAL VELOCITIES*

Date	Radial Velocity	O.−C.
1899.63	−21.6	−5.0
1903.51	−20.9	−2.3
1904.48	−21.8	−1.9
1905.52	−23.5	−1.9
1908.48	−30.9	−3.0
1910.75	−30.7	−1.2
1911.76	−31.2	−3.5

* *Publications of Lick Observatory*, **16**, 302, 1928.

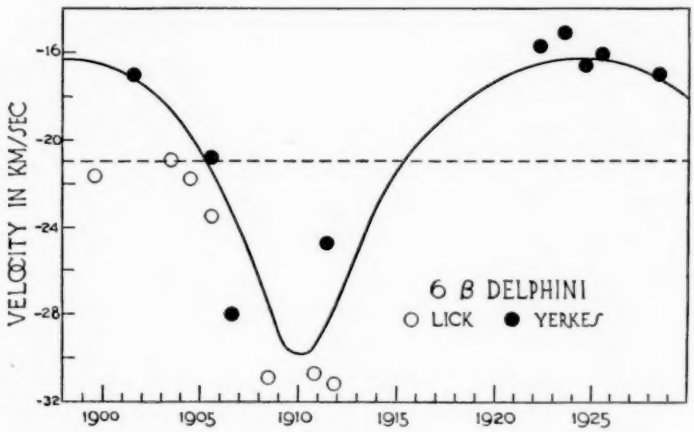

FIG. 2

inclination i is therefore positive according to convention. The visual orbit, as determined by Aitken,[1] and the spectroscopic elements are as follows:

Visual Orbit	Spectroscopic Elements
$P=26.79$ years	$K=$ 6.8 km/sec.
$T=1936.62$	$\gamma=-21.0$ km/sec.
$a=$ 0".480	$a \sin i=857{,}000{,}000$ km
$n=13°.438$	$\frac{m_2^3 \sin^2 i}{(m_1+m_2)^2}=0.263$
$e=0.350$	
$i=$ 62°.25	$\frac{m_2^3}{(m_1+m_2)^2}=0.379$
$\omega=351°.20$	
$\Omega=178°.55$	

[1] *Lick Observatory Bulletin*, **12**, 150, 1912.

From the foregoing elements, it is found that $a = 968{,}400{,}000$ km and $M/p = 13.5$.

The following list gives some determinations of the parallax of 6 β Delphini:

TABLE IV

Observer	Observatory	Parallax		Method
H. B. Steele	Sproul	+0.016	±0.011	Photographic
Adams and Joy	Mt. Wilson	+0.038		Spectroscopic
Van Biesbroeck and Pettit	Yerkes	+0.043	±0.006	Photographic
Adams	Mt. Wilson	+0.046		Spectroscopic
van Maanen	Mt. Wilson	+0.037	±0.008	Photographic

The mean of these values, with correction of +0".005 to the relative parallaxes, is +0".039. With this value of p, $M = 0.53$, that is to say, the two components of this system are about equal in mass.

The writer wishes to thank Professor Edwin B. Frost, Professor G. Van Biesbroeck, and Dr. Otto Struve for their suggestions and help during the progress of the work.

YERKES OBSERVATORY
June 27, 1928

EVIDENCE OF BORON IN THE SUN[1]

By SETH B. NICHOLSON and NICOLAS PERRAKIS

ABSTRACT

The *presence of boron in the sun has been established* by identifying certain lines in the *spectra of sun-spots* with lines in the *band spectrum of boric acid*. That boron should be *identified* in the sun *by the spectrum of its compounds* is not surprising since the elements carbon, nitrogen, and oxygen, which follow it in the periodic chart, were first identified in the sun by their *band spectra*. The *known* lines in the spectrum of atomic boron are in the ultra-violet where they *cannot be observed in the sun*.

Only the *strongest lines in the band spectrum* of boron appear in the *spot spectrum*. In the region of the boron bands the spot spectrum is very rich in lines, so that many of the boron lines fall near strong spot lines and cannot be measured. Only about 20 per cent of the lines investigated were identified with certainty, but *none of the strongest lines* of the boron bands *were definitely missing* from the spectra of spots. *The mean difference in wave-length for the identified lines was less than 0.006 A.*

Many of the elements have not been identified in the solar atmosphere, and it is interesting to see the difference in atomic structure between the identified and unidentified elements. The relation, which has already been pointed out by one of us,[2] between the atomic numbers of the elements and their ionization potentials, to which the character of their spectra is so closely related, is given in Figure 1. According to Russell, Dugan, and Stewart,[3] the spectra of the elements represented by circles have not yet been observed in the solar atmosphere. An examination of this graph shows that the inert gases *Ne*, *A*, *Kr*, *Xe*, and those elements whose external orbit systems are approximately closed, namely, *F*, *Cl*, *Br*, *I*, ... , have not been identified in the solar atmosphere; while, on the contrary, the elements *Li*, *Na*, *K*, *Rb*, ... , with atomic structures far enough from the model attributed to the inert gases, have been identified without doubt. In other words the elements of the fourth and sixth periods in the table of Mendeleff, which, unlike periods 2, 3, 5, and 7, do not end with a rare gas, are nearly all present in the sun. The unidentified elements which are the inert gases and their neighbors in the periodic chart are nearly all elements with high ionization potentials. There are, however, two notable exceptions—

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 370.

[2] Nicolas Perrakis, *Journal de Chimie Physique*, **24**, 120, 1927.

[3] *Astronomy*, **2**, 503, 1927.

helium and boron. The former, which has the highest ionization potential of all the elements, has long been known to exist in the sun; while boron, an element with relatively low ionization potential, had

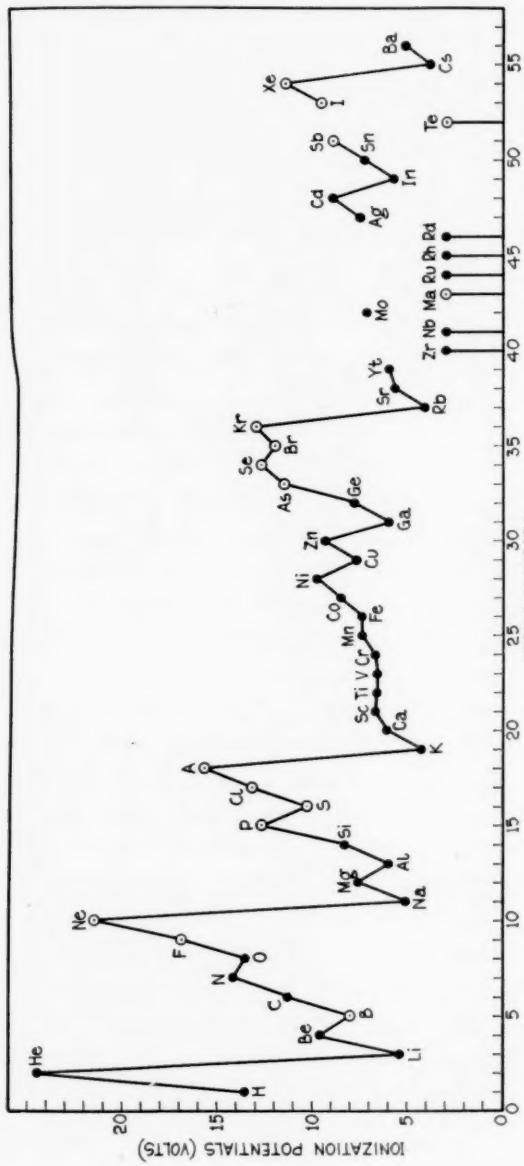

FIG. 1

never been observed there. Of the comparatively heavy elements from hafnium to uranium, which have been omitted from Figure 1, only two—*Th* and *Pb*—have been identified in the sun, although their ionization potentials are low, especially those of the radioactive series. One of these, radon, is, however, an inert gas. These heavy elements, most of which are subject to dissociation, may be totally absent from the sun's atmosphere or be localized in the lowest part of the reversing layer.

Absorption due to helium, the presence of which in the sun is normally shown only by the spectrum of the chromosphere, has been observed at D_3 in the neighborhood of active sunspots. A study is being made of the helium absorption, which, as might be expected on account of its high ionization potential, is strongest over the faculae near active spot groups. Helium must be very abundant in the sun to produce even a weak absorption line in these regions where the temperatures, although the hottest on the sun, are still much below those at which the absorption lines are a maximum for an element with the high ionization potential of helium.

The case of boron is, on the other hand, very different. This comparatively light element, with relatively low ionization potential, would probably have been detected in the sun long ago were it not for the fact that all the known lines in its atomic spectrum lie in the ultra-violet region where it is impossible to observe them in the solar spectrum. Carbon, nitrogen, and oxygen, which follow boron in the periodic chart of the elements, were first identified in the sun by their band spectra; and it seemed probable that boron, if present in the sun, might be detected by the spectra of its compounds. Since the ionization potential of boron is low, we may expect the spectra of its compounds to be much stronger in spots than in the hotter photosphere. In the region of the spectrum λ 4530 to λ 5800, where the strong bands of boron compounds are found, their identification in spots is difficult on account of the great number of other lines which also occur in that region, particularly lines produced by the band spectra of other elements, notably carbon, nitrogen, and oxygen. It seemed probable, therefore, that a careful comparison of the band spectrum of boron with the spectra of sun-spots might lead to the detection of this element in the sun.

The band spectrum of boron has been studied by Kühne,[1] and wave-lengths have been published by him to hundredths of an angstrom. Better wave-lengths were desirable, and these were obtained from a spectrogram of boric acid taken by Dr. King with the 15-foot concave-grating spectrograph. Iron-arc lines were used for standards, and, although only one plate was measured, the relative wave-lengths should not be in error by more than a few thousandths of an angstrom. Absolute wave-lengths are not necessary, since there will almost certainly be systematic differences in wave-length between the arc spectrum and the spot spectrum. In the preliminary survey all the lines of the boron bands between λ 5028 and λ 5137 were measured and compared with lines in the spectra of spots. For this comparison, spot spectra in the third order of the 75-foot spectrograph, with a dispersion of about 0.24 A per mm, were available. The spectra had been made with the polarizing apparatus which is used for the study of the Zeeman effect in spots.[2] Measures of the spot lines were made on three adjoining quarter-wave plates so that the effect of the magnetic field of the spot would be eliminated as far as possible. Band lines show little, if any, effect of the magnetic field in spots; and none of the spot lines which gave Zeeman displacements were considered. The lines which were used as standards in measuring the spot spectra had, in most cases, displacements due to the magnetic field, and the measures from individual spectra may show systematic deviations due to the imperfect elimination of the Zeeman displacements. The relative wave-lengths in the same spectra should, however, be little affected by such errors.

It was soon apparent from the preliminary survey that only the strongest lines of the boron bands were present in the spot spectra, and therefore only the strongest of the boron lines were measured over the whole range of the spectrogram. The intensities of the boron lines and of the spot lines were estimated as the wave-lengths were being measured. In the spot spectra the intensities were estimated as nearly as possible on the Rowland scale. In the spectrum of boric acid the intensities are on an arbitrary scale.

[1] *Zeitschrift für wissenschaftliche Photographie*, **4**, 173, 1906.

[2] Hale, Ellerman, Nicholson, and Joy, *Mt. Wilson Contr.*, No. 165; *Astrophysical Journal*, **49**, 153, 1919.

The results of the measurements are given in four tables. As has already been stated, the spot spectrum throughout the region

TABLE I

LINES BLENDED IN THE SPOT SPECTRUM

λ I A	Intensity	λ I A	Intensity	λ I A	Intensity
		(*a*)			
4652.408	5	4748.828	2d	5048.310	3
4655.972	4	4755.693	2d	5057.490	3
4658.734	3	4758.132	3db	5074.740	3
4666.245	4	4762.726	4	5077.865	3d
4680.719	4	4781.636	3db	5081.506	3
4682.347	3	4806.873	4db	5085.357	3d
4690.320	3	4811.591	4db	5089.358	3d
4694.061	4	4836.641	3	5089.481	3d
4698.353	4	4843.304	3	5093.590	3
4704.286	3	4852.933	2	5094.742	3
4711.582	3	4861.509	3	5112.345	3
4717.348	2d	4902.231	3	5128.017	3d
4736.595	4b	4924.462	2	5128.466	3d
4742.179	4b	4935.709	3	5134.191	3
		(*b*)			
5028.244	1	5067.783	2	5104.405	1
5028.726	0	5068.699	1	5107.362	1
5029.210	0	5070.867	1	5109.412	1d
5030.681	2	5071.103	2	5111.090	0d
5030.693	0	5072.364	0	5111.651	1
5033.270	0	5077.569	1	5115.476	0
5036.027	0	5078.393	1	5115.968	1d
5038.980	1	5079.492	2d	5120.020	1
5041.468	1	5082.279	1d	5121.691	0
5045.116	0	5084.389	2	5122.151	1
5045.356	1	5085.027	0	5123.557	1
5048.184	2	5086.305	1	5125.604	0
5048.428	1	5086.889	1	5125.784	0
5048.817	1	5087.184	1	5126.002	0
5049.884	1	5088.174	1	5130.249	2
5051.517	2	5089.043	1	5133.713	2
5053.325	1	5090.260	0	5136.311	0
5055.326	1	5090.547	1	5136.825	2
5056.265	2	5092.462	1	5137.398	1
5059.163	2	5097.623	1	5227.661	1
5059.835	1	5098.528	1	5231.572	1
5061.661	2	5100.190	2d	5236.340	0
5061.906	1	5100.000	0	5240.836	0
5062.156	0	5103.601	0	5260.046	2
5065.113	2	5104.143	1d	5263.725	2d

studied is very rich in lines. There are, on the average, about ten lines per angstrom, so that many accidental coincidences were to be

expected. Table I contains all the boron lines which were so nearly coincident with lines in the spot spectra that measures in the spot were impossible. The spot lines had such a large range of intensity that no constant difference of wave-length could be used in assigning lines to Table I. Part (*b*) of Table I contains the fainter lines of

TABLE II

LINES MOST PROBABLY IDENTIFIED

λ I A (Boron)	Intensity (Boron)	λ I A (Spot)	Intensity (Spot)	Δλ	Remarks
4656.836	3	4656.830	ood	−0.006	Near another line
4670.718	4	4670.723	o	+0.005	
4692.256	4b	4692.261	ooo	+0.007	
4729.400	3d	4729.391	oobd	−0.007	Perhaps a double line
4743.603	4b	4743.602	oo	+0.001	
4765.679	3	4765.677	oo	0.000	
4772.977	4	4772.974	o	−0.001	
4773.398	4	4773.396	oo	0.000	Between two close lines
4797.768	4	4797.769	oo	+0.003	
4847.874	3	4847.872	oo	−0.002	
4913.431	2d	4913.420	oooo	−0.011	
4923.487	3d	4923.491	oo	+0.004	
5034.349	3	5034.334	ooo	−0.012	
5046.637	2d	5046.639	ooo	+0.005	
5062.383	2	5062.379	oo	−0.001	
5064.365	3d	5064.366	ooo	+0.004	
5067.997	3	5067.999	oo	+0.005	
5073.219	2	5073.225	ooo	+0.009	
5094.977	2	5094.992	ooo	+0.010	
5097.978	3d	5097.968	oo	−0.015	
5099.606	2	5099.616	oo	−0.013	
5105.829	2	5105.833	oo	−0.009	
5106.974	2	5106.988	oo	+0.001	
5117.522	3	5117.533	ooo	−0.002	
5122.439	2	5122.445	oo	−0.007	
5122.880	3d	5122.891	ooo	−0.002	
5134.667	2	5134.669	oo	−0.011	
5245.234	2	5245.230	oooo	−0.004	

boron, for which only preliminary measures were made. The strongest lines and those for which there was some question about their identification in the preliminary survey were measured a second time, and their wave-lengths are given in part (*a*) of Table I. The only difference between the two parts of this table is that the wave-lengths of part (*a*) are probably more accurate than those of part (*b*).

Table II contains the lines which were identified in the spot spectra. The Δλ's in the fifth column are the differences in wave-

length between the boron lines, as measured in the laboratory and in the sun-spot, so corrected that the mean difference for each spot

TABLE III

LINES FOR WHICH IDENTIFICATION IS DOUBTFUL

λ I A (Boron)	Intensity (Boron)	λ I A (Spot)	Intensity (Spot)	Δλ	Remarks
4685.437	3	.....	.....	.....	Between two close lines. May be present
5037.171	0	5037.127	00	−0.041	
5040.152	2	5040.126	00	−0.023	
5042.077	2	5042.050	000	−0.024	
5053.819	2	5053.793	00	−0.023	
5054.238	0	5054.221	00	−0.014	
5057.651	3	5057.666	00	+0.018	
5065.865	3d	5065.884	00	+0.022	
5070.229	2d	5070.215	00	−0.011	
5074.120	1	5074.111	00	−0.006	
5077.133	0	5077.173	00	+0.043	
5081.214	2d	5081.214	00	+0.003	
5082.784	1	5082.785	00	+0.004	
5087.847	1d	5087.874	000	+0.022	
5100.433	0	5100.469	00	+0.023	
5102.217	2d	5102.250	00	+0.020	
5102.581	3	5102.634	00	+0.040	Near line of intensity 0 in spot
5114.623	1	5114.650	00	+0.014	
5117.099	3	5117.089	00	−0.023	
5123.857	2	5123.896	00	+0.026	
5126.401	0	5126.389	00	−0.025	
5135.130	1	5135.097	0	−0.046	

TABLE IV

LINES MISSING FROM SPOT SPECTRUM

λ I A	Intensity	Remarks
4841.422	2	Between two close lines. A very faint line may be present
5037.377	0	
5052.447	2	
5060.210	1	
5064.860	1	Fe line near
5093.083	1d	
5093.241	1d	
5109.947	1	
5111.949	1d	
5114.273	1d	

plate is zero. No lines were included in Table II for which the difference in wave-length between spot and boron is greater than 0.020 A or for which the difference in intensity is very small.

Table III contains lines which may be identical, but for which the intensities or wave-lengths indicate that they are probably blends with other spot lines.

Table IV contains the lines which were certainly missing from the spot spectra.

The average difference in wave-length between the lines of boric acid and those of the spot is 0.0056 A, less than would be expected for accidental coincidences, even in a spectrum as rich in lines as is that of the spot; and, since none of the strongest lines in the spectrum of boron were definitely missing from the spot spectra, the presence of boron in the sun seems established.

CARNEGIE INSTITUTION OF WASHINGTON
MOUNT WILSON OBSERVATORY
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ORBIT OF THE SPECTROSCOPIC BINARY 30 τ CANIS MAJORIS

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ABSTRACT

The orbital elements of this spectroscopic binary of *type O* were derived from 43 spectrograms, of which 33 were obtained at the Yerkes Observatory, 7 at the Lick Observatory, and 3 at the Dominion Observatory, Ottawa. The *spectrum* shows the lines of the *brighter component* only.

The *velocity of recession of the system* is 40.4 km/sec. The total *range in velocity* is 104 km/sec. The *period* is 154.80 days, longer than that of any other O-type binary. The *eccentricity* is 0.36. The *longitude of periastron* is 102°.5. The *foreshortened major semiaxis*, $a_1 \sin i$, is 103,700,000 km; assuming an average inclination and mass ratio, the corresponding *mean distance* of the two components of the system would be of the order of 2 astronomical units. The *mass function* is 1.86 $\odot$, which is normal for a binary of spectral type O, and corresponds to an *average total mass* of 40 times that of the sun.

This is the typical star for class Oe5 of the Harvard classification. Its spectrum is briefly described in the Introduction[1] to the *Henry Draper Catalogue;* a more detailed description of it is given by Miss Cannon[2] in the original paper on the classification of stellar spectra.

The position, for 1900, is $\alpha = 7^h\ 14^m.6$, $\delta = -24°46'$. Less than 24′ north of this $4^m.4$ star is the $4^m.9$ star 29 Can. Maj., the prototype of spectral class Oe. A comparative spectrophotometric study of these two bright O-type stars was made by Miss Cecilia H. Payne;[3] her paper gives also microphotograms of the two spectra.

When Professor E. B. Frost[4] announced the variable velocity of large range derived from the spectrograms of 29 Can. Maj., he remarked, in a footnote added to the proofsheets, that the radial velocity of 30 τ Can. Maj. also shows considerable variations.

The following orbit of 30 τ Can. Maj. is based on 43 spectrograms; the velocities from five plates secured at this observatory in 1906–1909 were published by O. J. Lee;[5] seven spectrograms were

[1] *Harvard Annals*, p. 6 of any one of the nine volumes, **91–99**.

[2] *Harvard Annals*, **28**, 150, 1901.

[3] *Harvard Bulletins*, No. 843, 11, 1927.

[4] *Astrophysical Journal*, **23**, 265, 1906. The binary character of 30 τ Can. Maj. was later independently discovered by H. D. Curtis; see *Lick Observatory Bulletins*, **6**, 145, 1911.

[5] *Astrophysical Journal*, **39**, 45, 1914. There is a misprint in this list of five velocities. Plate IB 974 was secured, in 1907, on Feb. 8 (not on Feb. 7), at 15^h48^m G.M.T.

obtained at the Lick Observatory[1] in 1907–1914; W. E. Harper[2] gave the measures of three plates taken at the Dominion Observatory (Ottawa) in 1917–1918; the last twenty-eight spectrograms were secured here in 1927–1928. Plates 32 and 33 are three-prism spectrograms taken with the Moffitt short-focus camera; spectrogram 37 was secured with three prisms and the Ross camera; the remaining thirty Yerkes spectrograms have a dispersion of one prism, corresponding to 30 A/mm at λ4500. The average time of exposure, on Eastman 40 plates, was 93 minutes.

One component only[3] could be measured on our spectrograms. In addition to the H and K lines of Ca^+, from 8 to 11 lines due to hydrogen, helium, silicon, and nitrogen could be measured on good plates. On our spectrograms the lines appear faint and diffuse, so that the probable error for a single plate designated as "good" comes out rather large, ±7.43 km/sec.

Table I contains the spectrographic material used. The time of mid-exposure is given in G.M.T. (counted from Greenwich noon to noon) for the early observations, and in U.T. (from Greenwich midnight to midnight) for the recent series of plates. The weights 1.0, 0.7, and 0.3 were assigned to good, fair, and poor plates, respectively. The phases are counted from J.D. 2425201.72 U.T., with a period $P = 154^d.80$ determined by trial from both early and recent observations, and adopted as giving a satisfactory representation of all available velocities. The residuals were computed with the adjusted orbital elements.

The observed velocities were grouped into 17 normal places, as shown in Table II. The phases are counted, as in Table I, from the adjusted epoch of periastron passage, J.D. 2425201.72 U.T. The residuals correspond to the adjusted orbital elements.

A free-hand velocity-curve was drawn through the normal places plotted with the adopted period of 154.80 days; the hodographic

[1] *Publications of the Lick Observatory*, **16**, 109, 1928. The velocity derived from the plate taken 1908, Jan. 12, is given as −17 km/sec. by W. W. Campbell, in *Lick Observatory Bulletins*, **6**, 145, 1911.

[2] *Publications of the Dominion Observatory*, **4**, 345, 1919.

[3] Double lines were seen only on the plate taken in 1908, according to *Lick Observatory Bulletins*, **6**, 145, 1911. The plate received the weight ½ in the *Lick Observatory Publications*, **16**, 109, 1928, where no reference to double lines is found.

TABLE I

RADIAL VELOCITIES OF 30 τ CANIS MAJORIS

No.	Date	Observer	Weight	Phase	Velocity km/sec.	O.−C. km/sec.	H & K km/sec.
	G.M.T.	Early Observations					
1.....	1906 Mar. 23.597	F	0.3	141.977	+77.4	+ 1.9	.....
2.....	Mar. 30.586	F	1	148.966	+49.4	− 2.7	.....
3.....	Apr. 2.562	F	1	151.942	+37.9	− 0.7	.....
4.....	1907 Feb. 6.582	Lick Obs.	1	152.362	+37	+ 0.4	.....
5.....	Feb. 8.658	F	0.3	154.438	+ 0.4	−26.3	.....
6.....	1908 Jan. 12.635	Lick Obs.	0.3	28.015	−29	−20.0	.....
7.....	1909 Mar. 1.661	F	1	132.441	+91.5	+ 3.8	.....
8.....	1910 Nov. 4.021	Lick Obs.	1	125.601	+93.5	+ 5.5	.....
9.....	Nov. 15.995	Lick Obs.	1	137.575	+79	− 4.4	.....
10.....	1913 Dec. 2.83	Lick Obs.	1	12.01	− 8.7	+ 4.1	.....
11.....	Dec. 29.75	Lick Obs.	1	38.93	− 2	− 5.6	.....
12.....	1914 Feb. 2.71	Lick Obs.	1	73.89	+51	+ 7.1	.....
13.....	1917 Dec. 11.833	Ottawa	0.7	88.813	+32	−27.2	.....
14.....	1918 Jan. 3.733	Ottawa	0.7	111.713	+71	− 8.4	.....
15.....	Feb. 20.604	Ottawa	0.7	4.784	+ 1	− 3.6	.....
	U.T.	New Observations					
16.....	1927 Dec. 17.256	P, S	1	30.536	− 1.8	+ 4.5	+30.0
17.....	Dec. 20.255	H, S	1	33.535	+14.0	+16.9	+17.0
18.....	Dec. 21.278	σ, P, S	1	34.558	−13.1	−11.4	+31.4
19.....	Dec. 21.350	σ, S	1	34.630	+ 6.3	+ 7.9	+30.8
20.....	Dec. 25.292	B, σ, S	1	38.572	− 1.5	− 4.7	+34.6
21.....	1928 Jan. 3.295	B, σ, S	1	47.575	+21.2	+ 7.1	+23.1
22.....	Jan. 7.256	σ, S	0.7	51.536	+27.3	+ 8.5	.....
23.....	Jan. 8.309	B, σ, S	1	52.589	+21.0	+ 0.9	+34.4
24.....	Jan. 12.226	B, S	0.3	56.506	+20.7	− 4.0	.....
25.....	Jan. 21.217	σ, S	1	65.497	+16.5	−18.3	+34.4
26.....	Jan. 22.237	B, S	1	66.517	+35.2	− 0.7	+23.3
27.....	Jan. 22.299	B, σ, S	0.3	66.579	+32.7	− 3.3	.....
28.....	Jan. 23.203	σ, S	1	67.483	+29.6	− 7.4	+38.3
29.....	Jan. 31.274	B, σ, S	0.7	75.554	+55.8	+10.2	.....
30.....	Feb. 5.231	σ, S	0.7	80.511	+62.0	+11.2	.....
31.....	Feb. 6.161	B, H, S	0.3	81.441	+59.6	+ 7.9	.....
32.....	Feb. 24.075	σ, S	1	99.355	+67.0	− 2.3	.....
33.....	Feb. 24.126	σ, S	0.7	99.406	+42.6	−26.7	.....
34.....	Mar. 3.183	P, H, S	1	107.463	+93.7	+17.2	+26.8
35.....	Mar. 4.175	σ, S	1	108.455	+88.8	+11.4	+13.0
36.....	Mar. 5.113	P, S	1	109.393	+87.1	+ 9.0	+34.9
37.....	Mar. 8.126	σ, P, S	0.3	112.406	+95.4	+14.9	.....
38.....	Mar. 18.136	P, S	0.3	122.416	+79.3	− 7.6	.....
39.....	Mar. 19.117	σ, P, S	1	123.397	+85.6	− 1.7	.....
40.....	Mar. 23.093	σ, P, S	1	127.373	+85.7	− 2.6	+24.5
41.....	Mar. 31.083	σ, P, S	1	135.363	+78.7	− 7.1	+27.4
42.....	Apr. 10.072	σ, P, S	1	145.352	+68.7	+ 2.8	+26.2
43.....	Apr. 15.065	σ, P, S	0.7	150.345	+59.6	+13.6	+25.8

NOTE.—The names of the observers are abbreviated as follows: B=S. B. Barrett, F=E. B. Frost, H=C. Hujer, P=A. Pogo, σ=O. Struve, S=F. R. Sullivan. The Yerkes spectrograms were measured by Struve.

method of Laves, as modified by Pogo,[1] was used for determining preliminary orbital elements. For the adjustment of these elements, a least-squares solution for five unknowns was made by Pogo. The

TABLE II

NORMAL PLACES OF 30 τ CANIS MAJORIS

No.	Mean Phase (days)	Mean Velocity (km/sec.)	O.−C. (km/sec.)	Wt.	Interval		Plates
					Days	Percentage of P	
1.....	4.78	+ 1.0	− 3.6	0.7	.....	.....	15
2.....	12.01	− 8.7	+ 4.1	1.0	.....	.....	10
3.....	34.79	− 1.1	+ 0.3	6.3	10.92	7.05	6, 16, 17, 18, 19, 20, 11
4.....	51.06	+22.5	+ 4.2	3.0	8.93	5.77	21, 22, 23, 24
5.....	66.51	+27.6	− 8.3	3.3	1.99	1.29	25, 26, 27, 28
6.....	74.58	+53.0	+ 8.4	1.7	1.66	1.07	12, 29
7.....	84.09	+49.2	− 5.2	1.7	8.30	5.36	30, 31, 13
8.....	99.38	+57.0	−12.3	1.7	0.05	0.03	32, 33
9.....	109.31	+87.0	+ 8.9	4.0	4.94	3.19	34, 35, 36, 14, 37
10.....	125.16	+87.5	− 0.4	3.3	4.96	3.20	38, 39, 8, 40
11.....	132.44	+91.5	+ 3.8	1.0	.....	.....	7
12.....	136.47	+78.8	− 5.9	2.0	2.21	1.43	41, 9
13.....	141.98	+77.4	+ 1.9	0.3	.....	.....	1
14.....	145.35	+68.7	+ 2.8	1.0	.....	.....	42
15.....	149.53	+53.6	+ 4.0	1.7	1.38	0.89	2, 43
16.....	152.15	+37.4	− 0.3	2.0	0.42	0.27	3, 4
17.....	154.44	+ 0.4	−26.3	0.3	.....	.....	5

TABLE III

ORBITAL ELEMENTS OF 30 τ CANIS MAJORIS

Element	Preliminary	Correction	Adjusted	Probable Error
γ	+41 km/sec.	−0.59 km/sec.	+40.4 km/sec.	.....
P.....	$154^d.80$	(adopted)	$154^d.80$	.....
T.....	J.D.2425200.00 U.T.	$+1^d.72$	J.D.2425201.72 U.T.	$\pm 2^d.21$
ω.....	95°	+7°.5	102°.5	±7°.1
e.....	0.35	+0.006	0.36	±0.038
K.....	50 km/sec.	+2.08 km/sec.	52.1 km/sec.	±2.15 km/sec.
$a_1 \sin i$.....	.....	.....	103,700,000 km	.....
$\frac{m_2^3}{(m_1+m_2)^2}\sin^3 i$	.....	.....	$1.86\odot$	.....

method of F. Schlesinger[2] was used in the computation of the coefficients of the normal equations. The improvement of the representation was slight, the sum of the weighted squares of the residuals

[1] *Astrophysical Journal*, **67**, 262, 1928.

[2] *Publications of the Allegheny Observatory*, **1**, 33, 1908.

being reduced from 231 to 220. The corrections to the preliminary elements are correspondingly small. The probable error of a normal velocity of unit weight is ±2.96 km/sec. The probable errors of the adjusted elements are given in Table III.

The velocity-curve computed with the adjusted elements is shown in Figure 1. The dots represent normal velocities. The final velocity-curve was used for the determination, by the hodographic

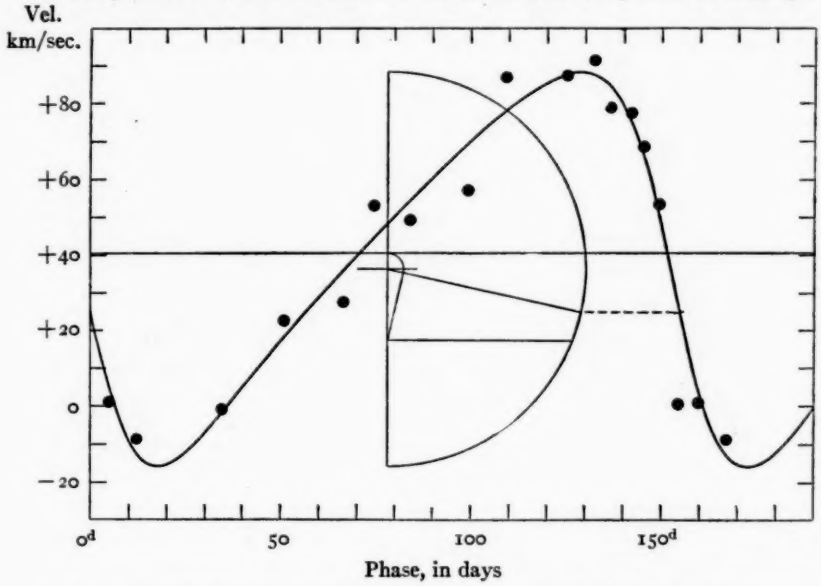

FIG. 1.—Velocity-curve and hodograph of 30 τ Canis Majoris. Dots represent normal places. Phase zero corresponds to J.D. 2,425,201.72 U.T., epoch of periastron passage.

construction, of the major semi-axis of the inclined absolute orbit of the principal star, and of the mass function.

The mean velocity corresponding to the H and K lines of Ca^+, is +28.0 km/sec. This value is considerably larger than the component due to the motion of the solar system, +19.0 km/sec. The remainder of +9 km/sec is fully explained by the rotation of the Galaxy, as will be shown in a paper by B. P. Gerasimovič and O. Struve.[1] The velocity of the center of mass is still larger, $\gamma = +40.4$ km/sec.

[1] To be published in the *Astrophysical Journal*, **69**, 1929.

Among the known spectroscopic binaries of spectral class O, this star has the longest period, $P=154.80$ days; the second longest period, $P=48.608$ days, belongs to B.D.44°3639.

The eccentricity, $e=0.36$, of 30 τ Can. Maj. agrees well with the long period, and is exceeded, among the O-type binaries, only by the abnormally high eccentricity, $e=0.755$, of ι Orionis.

The system 30 τ Can. Maj. has not been observed as an eclipsing binary, and only one component appears on our spectrograms. If we assume that $\sin^3 i=0.65$, and $m_2/m_1=0.7$, our mass function, $f(m)=1.86\odot$, leads to $m_1=24\odot$, $m_2=17\odot$, or a total mass of about 40 times that of the sun, agreeing well with the order of mass of other O-type binaries.

The value of $a_1 \sin i$ is larger than that of any other O-type binary. Under the foregoing assumptions concerning the inclination of the orbit and the ratio of the masses, the mean distance of the two components would be of the order of 2 astronomical units.

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